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HIGH CYCLE FATIGUE (HCF) SCIENCE AND TECHNOLOGY PROGRAM 1998 ANNUAL REPORT

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13. ABSTRACT *(Maximum 200 Words)*
This second annual report of the National Turbine Engine High Cycle Fatigue (HCF) Program is a brief review of work completed, work in progress, and technical accomplishments. This program is a coordinated effort with participation by the Air Force, the Navy, and NASA. The technical efforts are organized under seven Action Teams including: Materials Damage Tolerance Research, Forced Response Prediction, Component Analysis, Instrumentation, Passive Damping Technology, Component Surface Treatments, and Aeromechanical Characterization. Daniel E. Thomson, AFRL/PRTC, Wright-Patterson AFB, is the Program Manager.

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FOREWORD

This document, the second annual report of the National Turbine Engine High Cycle Fatigue (HCF) Science and Technology (S&T) Program, is a summary of the objectives, approaches, and technical progress of ongoing and planned future efforts.

High cycle fatigue (HCF) results from vibratory stress cycles induced from various aeromechanical sources. The frequencies can be thousands of cycles per second. HCF is a widespread phenomenon in aircraft gas turbine engines that historically has led to the premature failure of major engine components (fans, compressors, turbines) and in some instances has resulted in loss of the total engine. HCF costs the Air Force about $100 million a year.

The HCF S&T Program officially began in December 1994. The purpose of this national effort was to help eliminate HCF as a major cause of engine failures. The Program is directed by an Air Force led steering committee consisting of representatives from the Air Force, the Navy, and NASA, along with an adjunct industry advisory panel. The Organizational Structure of the HCF Team is shown below.

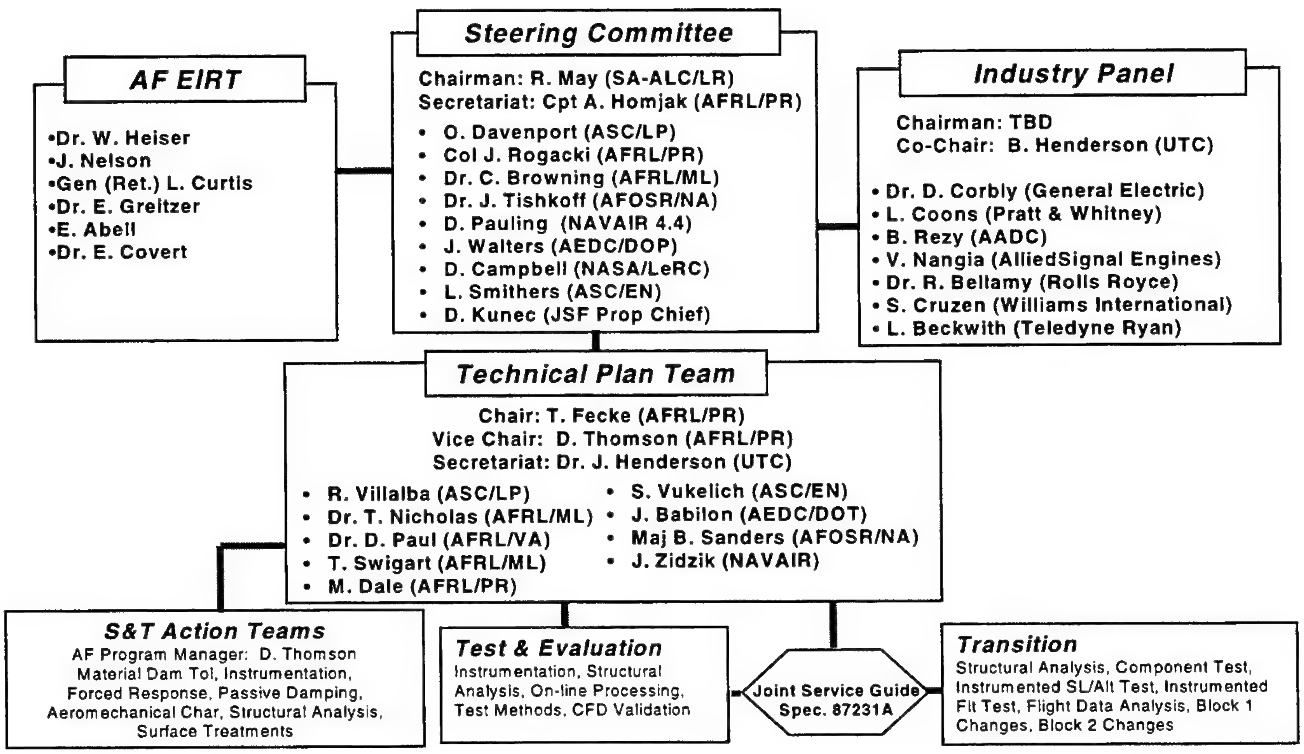


FIGURE 1. HCF Team Organizational Structure

The HCF S&T Program is specifically directed at supporting the Integrated High Performance Turbine Engine Technology (IHPTET) Program, and one of its goals: to reduce engine maintenance costs. This program will try to achieve that goal through technical action team efforts targeted at a 50% reduction of HCF-related maintenance costs. In addition, the program could contribute to a reduction in HCF-related "real" development costs of over 50%. When combined with the Test and Evaluation (T&E) program, and future health monitoring approaches, the HCF S&T program should ensure the

production of much more damage-tolerant high-performance engines, and essentially eliminate HCF-related engine/aircraft mishaps.

The specific component objectives of the HCF S&T program are listed below:

	Fans	**Compressors**	**Turbines**
Determine Alternating Stress Within…	20%	25%	25%
Damp Resonant Stress By…	60%	20%	25%
Reduce Uncertainty in Capability of Damaged Components by…	50%	50%	50%
Increase Leading Edge Defect Tolerance…	15x (5-75 mils)	n/a	n/a

The technical efforts are organized under seven action teams:

- Component Surface Treatments
- Materials Damage Tolerance Research
- Instrumentation
- Component Analysis
- Forced Response Prediction
- Passive Damping
- Aeromechanical Characterization

Over the last several years, the technologies developed under the High Cycle Fatigue (HCF) Science and Technology (S&T) Program have helped solve several difficult field engine programs. As a result, we are now seeing considerably fewer major HCF events.

Overall excellent progress in several HCF technology areas has provided the potential to drastically reduce overall engine maintenance costs. However HCF is a very difficult technology challenge that has continued to evolve multiple technology development and transition risks. New efforts are currently being defined to attack the most critical technology readiness issues even more aggressively.

The HCF S&T Program continues as a very high priority national effort. Meeting the total technology challenge could essentially eliminate engine HCF-related aircraft mishaps and greatly enhance overall aircraft system readiness.

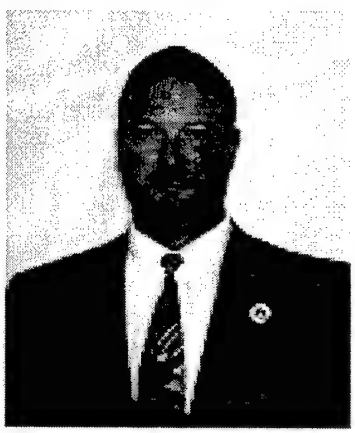
Your comments regarding the work reported in this document are welcome, and may be directed to Mr. Brian Garrison of Universal Technology Corporation (garrisbl@wl.wpafb.af.mil, 937-255-5003), or Mr. Daniel Thomson, the HCF Program Manager, of the Air Force Research Laboratory, Propulsion Directorate (AFRL/PRTC, Daniel.Thomson@pr.wpafb.af.mil, 937-255-2081).

1.0 COMPONENT SURFACE TREATMENTS

BACKGROUND

The Component Surface Treatments Action Team (Surface Treatments AT) has the responsibility of fostering collaboration between individual HCF surface treatment efforts with the goal of increasing leading edge defect tolerance by 15x (5 mils to 75 mils). The Surface Treatments AT provides technical coordination and communication between active participants involved in Laser Shock Peening (LSP) and related technologies. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Surface Treatments AT members meet as required (estimated quarterly) to review technical activities, develop specific goals for LSP programs, and coordinate with the Technical Plan Team (TPT) Industry Advisory Panel (IAP). The Chairman (or Co-Chair) of the Surface Treatments AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in surface treatment technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

ACTION TEAM CHAIRS



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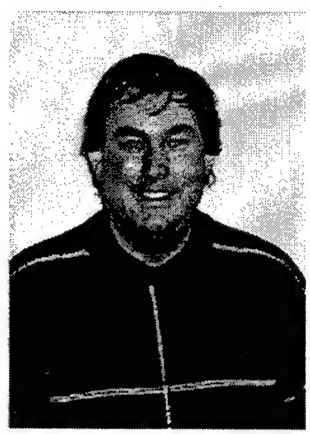

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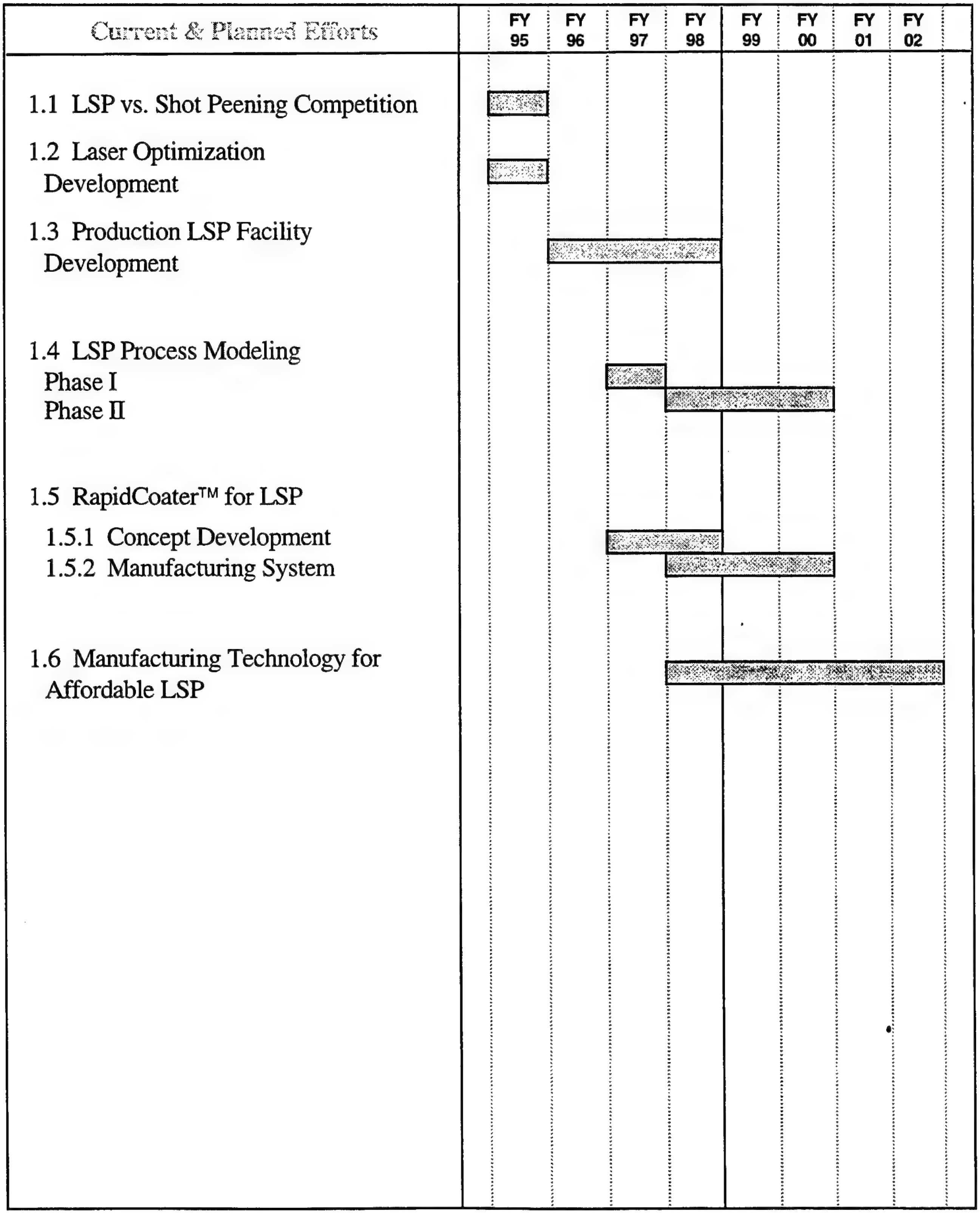
INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Component Surface Treatments Schedule



1.1 Laser Shock Peening (LSP) vs. Shot Peening Competition

FY 95

DESCRIPTION / PROGRESS

In September 1995, a comparative study between a new surface treatment technology called "Laser Shock Peening" (LSP), and an established surface treatment technology called "shot peening," was conducted. This study evaluated the damage tolerance improvements produced by these processes, specifically rating their influence for enhancing the fatigue life of turbine engine fan blades damaged by foreign objects (FOD). Critical blade characteristics, such as surface finish, change in aerodynamic profile, and manufacturability, were factored into the evaluation. The test matrix was configured to make the assessment as realistic and objective as possible. The resulting data showed that damaged Laser Shock Peened F101 fan blades with a 250-mil notch actually demonstrated greater fatigue strength than the baseline undamaged untreated fan blades (Fig. 2). Figure 3 describes the Laser Shock Peening process in more detail.

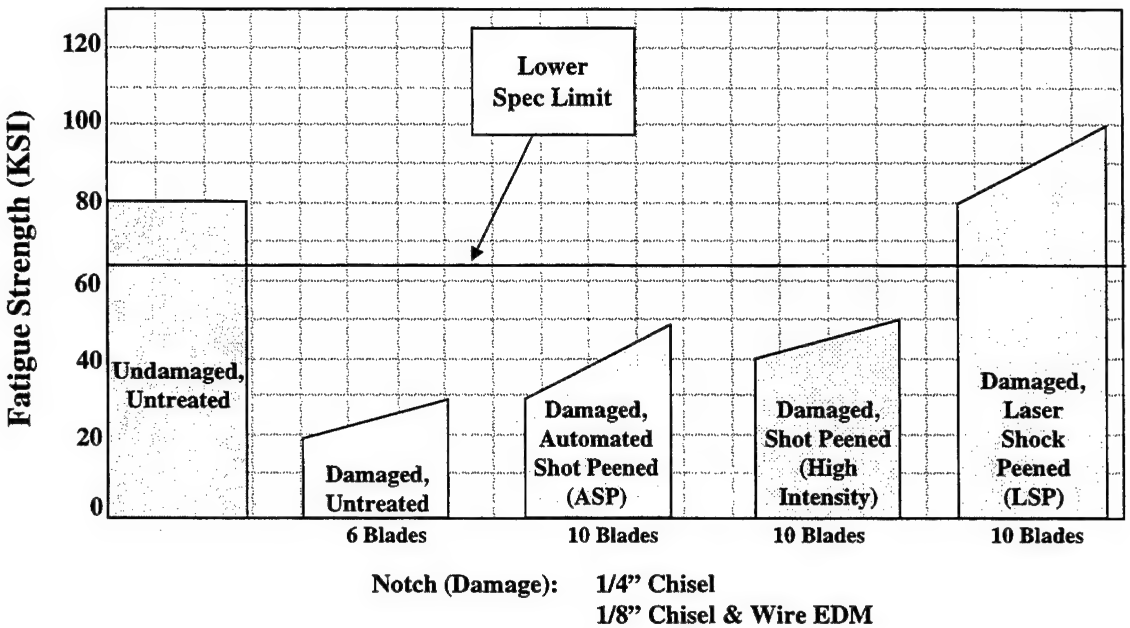


FIGURE 2. Damage Tolerance Data Indicating That Fatigue Strength of LSP'd Blades Is Equal to or Better Than That of Undamaged, Untreated Blades

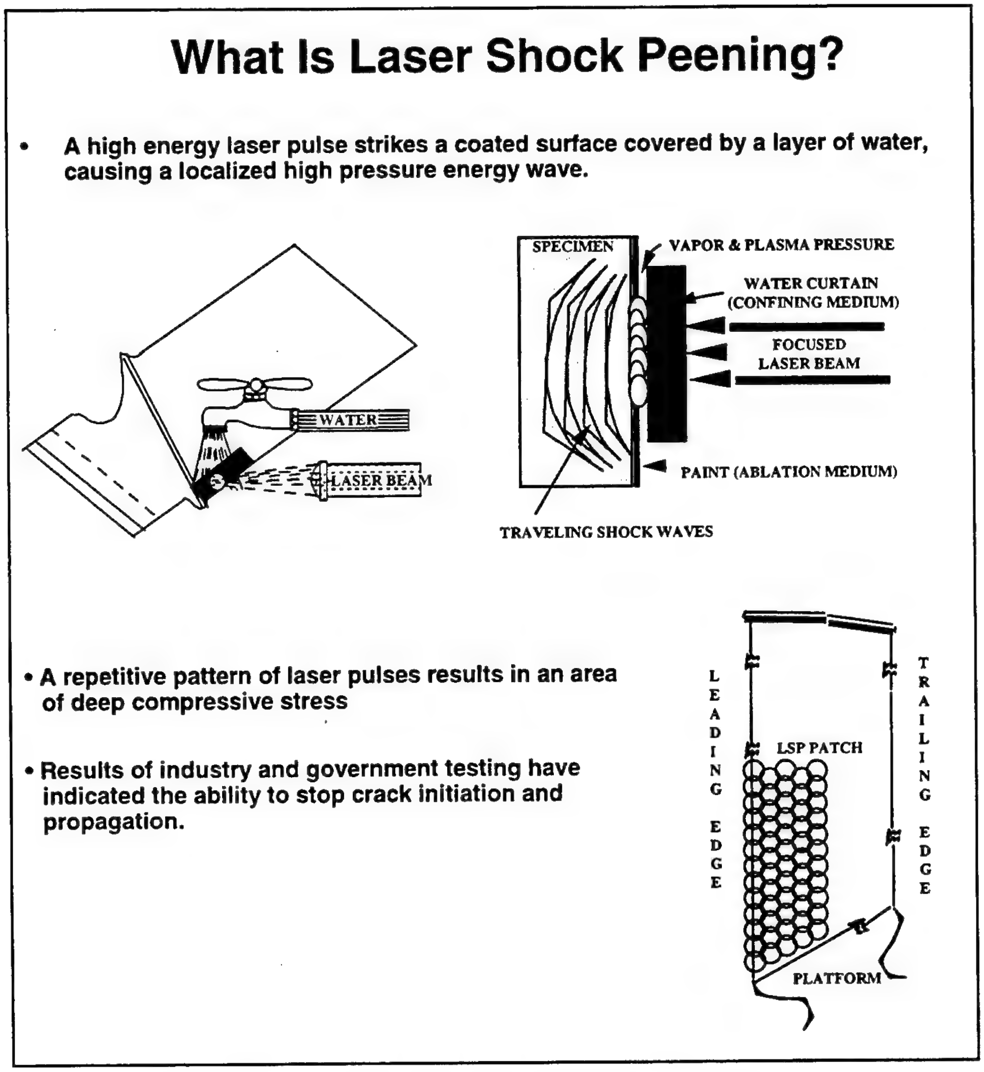


FIGURE 3. What Is Laser Shock Peening?

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1.2 Laser Optimization Development

FY 95

DESCRIPTION / PROGRESS

The primary objective of this program was to demonstrate the effectiveness of laser peening with elliptical and circular spots in terms of its ability to increase the fatigue life of an airfoil. A secondary objective was to demonstrate the ability to sharpen the rise time of the laser pulse using an optical switch, rather than using the traditional aluminum blow-off foil. Airfoil-shaped test specimens were laser peened using elliptical spots and circular spots and fatigue tested by the Air Force. A study of the rise time of the temporal laser pulse was conducted to confirm that an optical switch could modify the rise time of the laser pulse as effectively as an aluminum blow-off foil. An aluminum blow-off foil has traditionally been used to sharpen the leading edge of the laser pulse. A sharp rise time is important for many LSP conditions because it increases the peak pressure of the shock wave. Both elliptical and circular spots showed significant increases in fatigue life. A rise time comparable to the rise time generated with an aluminum blow-off foil was demonstrated (Fig. 4). Using the optical switch would eliminate concerns over the presence of aluminum vapor produced by the aluminum blow-off foil and the associated risks involving the health of personal and optical-component damage. It also increases the repeatability of the process.

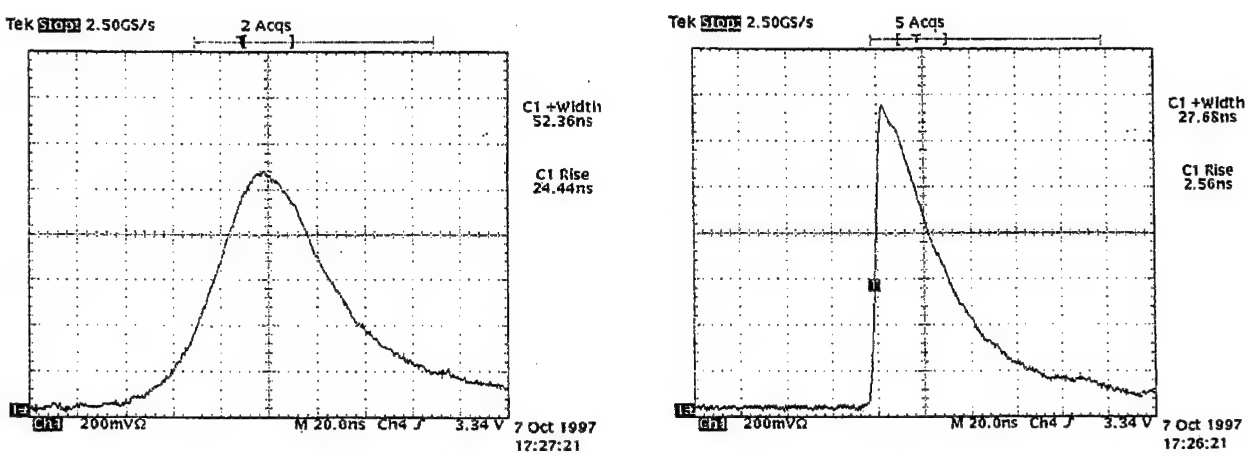

FIGURE 4. Peak Rise Time Before & After Laser System Modifications

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1.3 Production LSP Facility Development

FY 96-98

DESCRIPTION / PROGRESS

The primary objective of this program was to design and develop a Prototype Production Laser (PPL) capable of low levels of production. There were no commercially available lasers capable of meeting the requirements of the laser peening process. The program had three phases:

Phase I: Using working laboratory prototype lasers for the baseline design, the design was reviewed, outstanding technical issues related to the design were resolved, and the laser design was finalized. Specific technical issues to be resolved included:

1. The optical layout of the laser.
2. What system diagnostics would be used.
3. The mechanical design for the laser enclosure and electrical cabinets.

Phase II: Component acquisition, assembly, and subsystem checkout were accomplished during Phase II.

Phase III: Final laser system checkout and demonstration were accomplished in Phase III.

The system, consisting of the laser, the facility, and the process (Fig. 5) was successfully demonstrated in January 1998, and the laser is now available for use by the Air Force and industry.

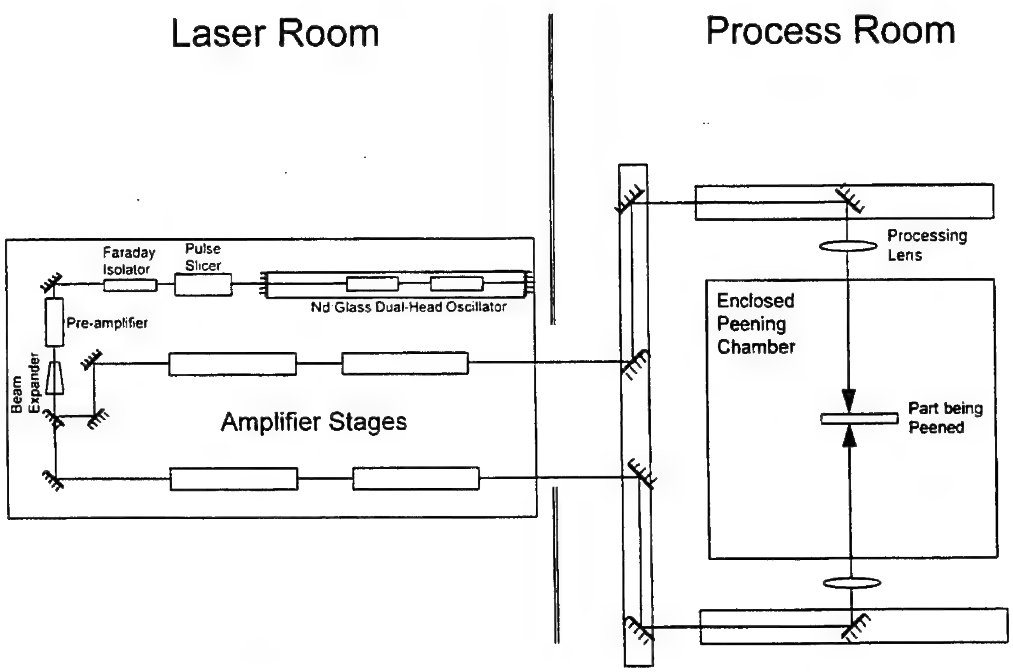

FIGURE 5. Schematic of Laser System Operations

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1.4 LSP Process Modeling

FY 97-00

DESCRIPTION / PROGRESS

In Phase I (FY 97) of this two-phase program, it was demonstrated that a residual stress profile could be modeled for a single laser spot. The objectives of Phase II (FY 98-00) are (1) to develop models for predicting the in-material residual stress profiles produced by multiple-spot Laser Shock Peening, (2) to verify and validate the residual stress profiles by comparison to experimental measurements, and (3) to gather appropriate data for input to the models.

Models for thin, intermediate, and large section thicknesses have been developed. The thin and intermediate section thicknesses are modeled with two-sided laser peening, whereas the thick section is laser peened from one side. Several constitutive equations for the material of interest have been explored and tested with the models.

Model verification will be based on the comparison of residual stress measurements performed on LSP'd coupons with those predicted by the model, as described in Figure 6. Sensitivity of the residual stress profiles to laser peening parameters is being analyzed and compared to experimental measurements. The residual stress profiles developed in a part depend on the material, the geometry and the laser peening parameters.

Based on the modeling results, process optimization schemes will be developed and outputs will be provided for damage tolerance analysis.

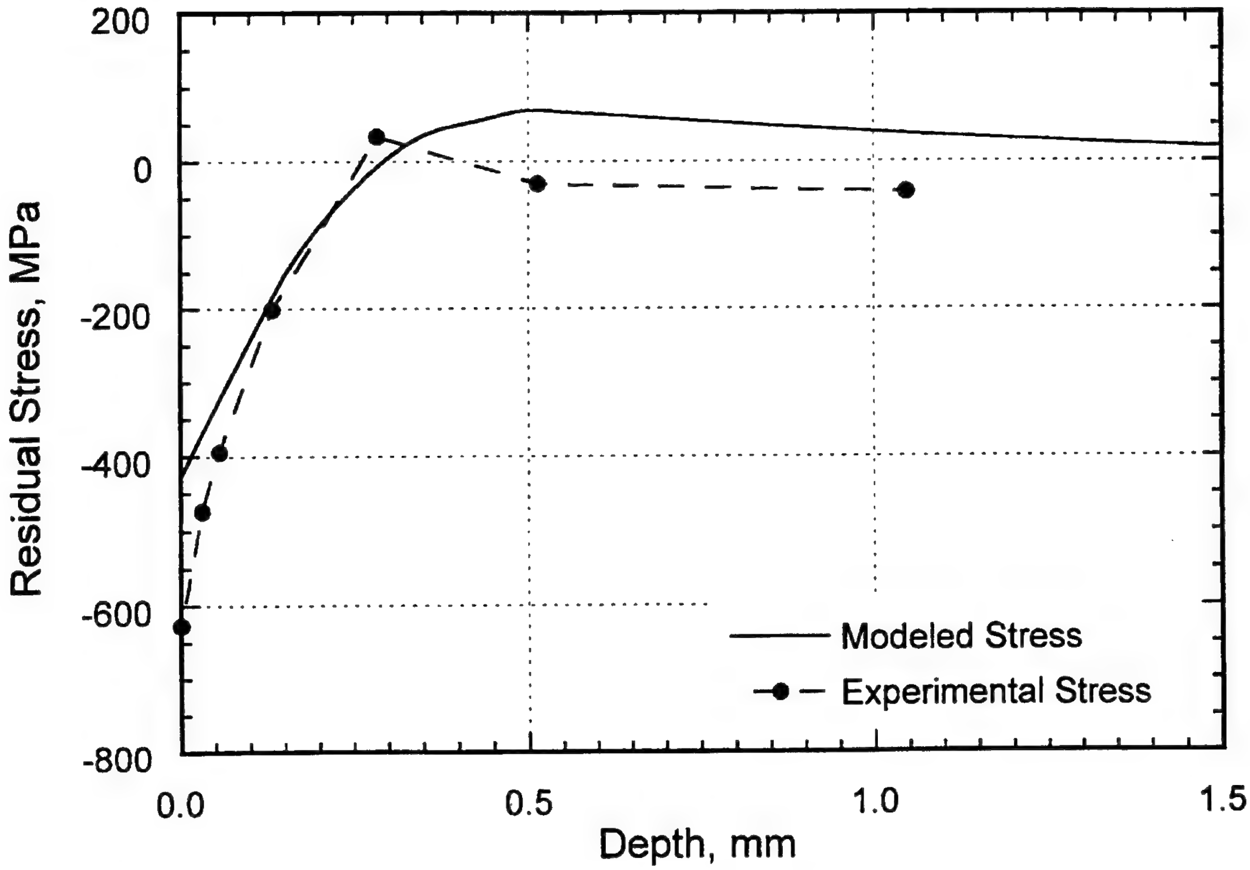

FIGURE 6. Comparison of Modeled and Experimental Residual Stresses for Estimated Similar Pressure Conditions

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1.5 RapidCoater™ for LSP
FY 97-00

DESCRIPTION / PROGRESS

One of the significant shortcomings of the current Laser Shock Peening process is slow processing, which is primarily due to the inability to remove the opaque overlay (paint) rapidly. Current practice requires the application and removal of the paint outside of the laser workstation. Under current practice, a part that requires multiple shots must be transported back and forth several times, from the laser workstation where it is peened, to a separate area where the overlay is removed, then back to the laser workstation, and so on. Sections 1.5.1 and 1.5.2 below explain what is being done to solve this problem. Section 1.5.1 describes the development, selection, and demonstration of a prototype system to rapidly remove the overlay system. Section 1.5.2 describes the development of a production system. The points of contact and participating organizations listed above apply to both of these efforts.

1.5.1 Rapid Overlay Concept Development
FY 97-98

DESCRIPTION / PROGRESS

The objectives of this program were to identify and evaluate promising methods for applying and removing the opaque overlay rapidly during laser peening.

Two coating application methods were investigated, (i) water soluble paint applied with a spray gun, and (ii) paint or ink application with an ink jet. The water-soluble paint/spray gun application method was selected as the most promising approach. The rapid overlay system concept was developed around this method. The rapid overlay demonstration test unit was assembled and tested to provide a working demonstration of the concept. The demonstration, which consisted of sequential application of the paint overlay, application of the overlay water film, firing the laser, and removal of the paint overlay in continuous, repetitive cycles, was successful. The successful demonstration system has been designated the RapidCoater™ System.

1.5.2 Development of a RapidCoater™ Manufacturing System
FY 98-00

DESCRIPTION / PROGRESS

The objective of this recent new start is to develop a rapid-overlay-removal manufacturing system to be integrated into a production laser peening system. The production RapidCoater™ System should accommodate a range of parts and operate reliably at the laser repetition frequency. Another objective is to develop a control system that will monitor the coating process and interface with the laser control system.

The mechanical system, consisting of the overlay applicator heads, the manipulator arm, and the overlay supply system, is currently being designed, and will be developed in the near future. The control and image systems will be designed, developed, tested, and integrated with the RapidCoater™ System in the near future as well. Upon successful completion of this step, the operational systems

will be integrated into the prototype production laser. Optical beam shaping to provide a square spot on the part surface will be evaluated, and if successful, integrated into the production prototype laser. In addition, optimization of the paint formulation for laser peening, and the impact of different part geometries on the design of the applicator heads will be evaluated.

The ultimate objective of the Component Surface Treatment Action Team and of all the efforts described in this section is to develop an affordable Laser Shock Peening system. The relationship of all these efforts is shown below in Figure 7.

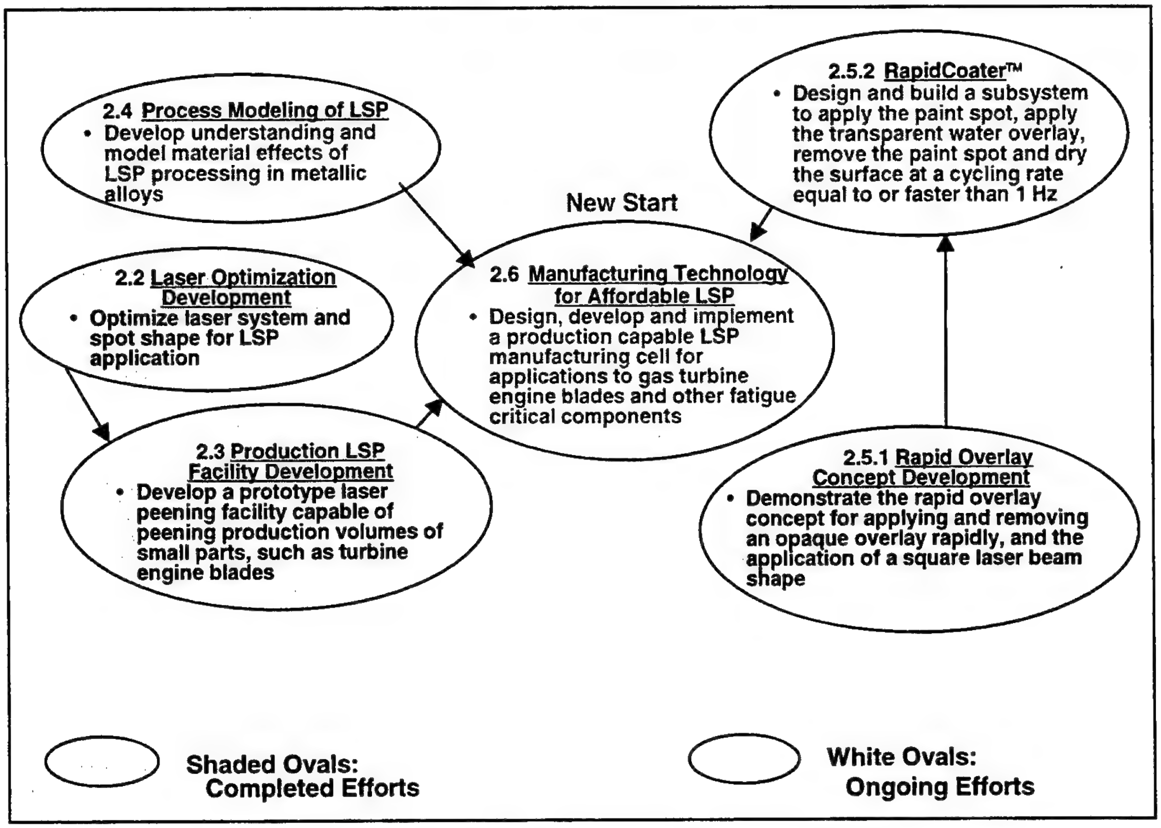

FIGURE 7. Interrelationship between LSP Programs

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1.6 Manufacturing Technology for Affordable LSP

FY 98-02

DESCRIPTION / PROGRESS

The main activity of this recent new start has been to prepare the facility for the various technical activities. The technical challenges associated with this program are all related to transitioning a prototype production facility into a full manufacturing facility. Additionally, the development and implementation of new (or improved) controls and monitors into the manufacturing facility will present individual technical challenges. This program has three phases.

Phase I: The purpose of Phase I is to mitigate the risks associated with the transition to manufacturing. This phase is divided into three areas:

1. Development and testing of new (or improved) controls and monitors, which will be used to increase the process reliability and reduce processing costs. Specifications for the primary monitors (energy, temporal profile, and spatial profile) are currently being developed.
2. Development of prototype small-parts and large-parts peening cells. This effort began in late 1998.
3. Initial commercialization planning and new application development. This is scheduled to begin 1999.

Phase II: Phase II is the final design and build phase for the laser and a small-parts peening cell. This phase is divided into two areas:

1. Fabrication and integration of a manufacturing cell consisting of the laser system and a small-parts peening cell. This includes the down-selection and integration of the controls and monitors developed in Phase I.
2. Demonstration of the LSP manufacturing cell. This is scheduled to begin in fiscal year 2001.

Phase III: Phase III is the commercial development phase. The objective is to identify new applications in several market sectors, including the aerospace, medical, and automotive sectors. This is scheduled to begin in fiscal year 2000.

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2.0 MATERIALS DAMAGE TOLERANCE RESEARCH

BACKGROUND

The Materials Damage Tolerance Research Action Team (Materials AT) is responsible for fostering collaboration between individual HCF damage tolerance research efforts, with the goal reducing the uncertainty in the capability of damaged parts by 50%. The Materials AT will provide technical coordination and communication between active participants involved in HCF life prediction, crack nucleation and propagation modeling, fracture mechanics methodology development, and the evaluation of surface treatment technologies. Annual technical workshops will be organized and summaries of these workshops will be disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Materials AT members will meet as required (estimated quarterly) to review technical activities, develop specific goals for materials damage tolerance research projects, and coordinate with the Technical Planning Team (TPT) and the Industry Advisory Panel (IAP). The Chairman (or Co-Chair) of the Materials AT will keep the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT will include members from government agencies, industry, and universities who are actively involved in materials damage tolerance technologies applicable to turbine engine HCF. The team is intended to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT will change as individuals assume different roles in related programs.

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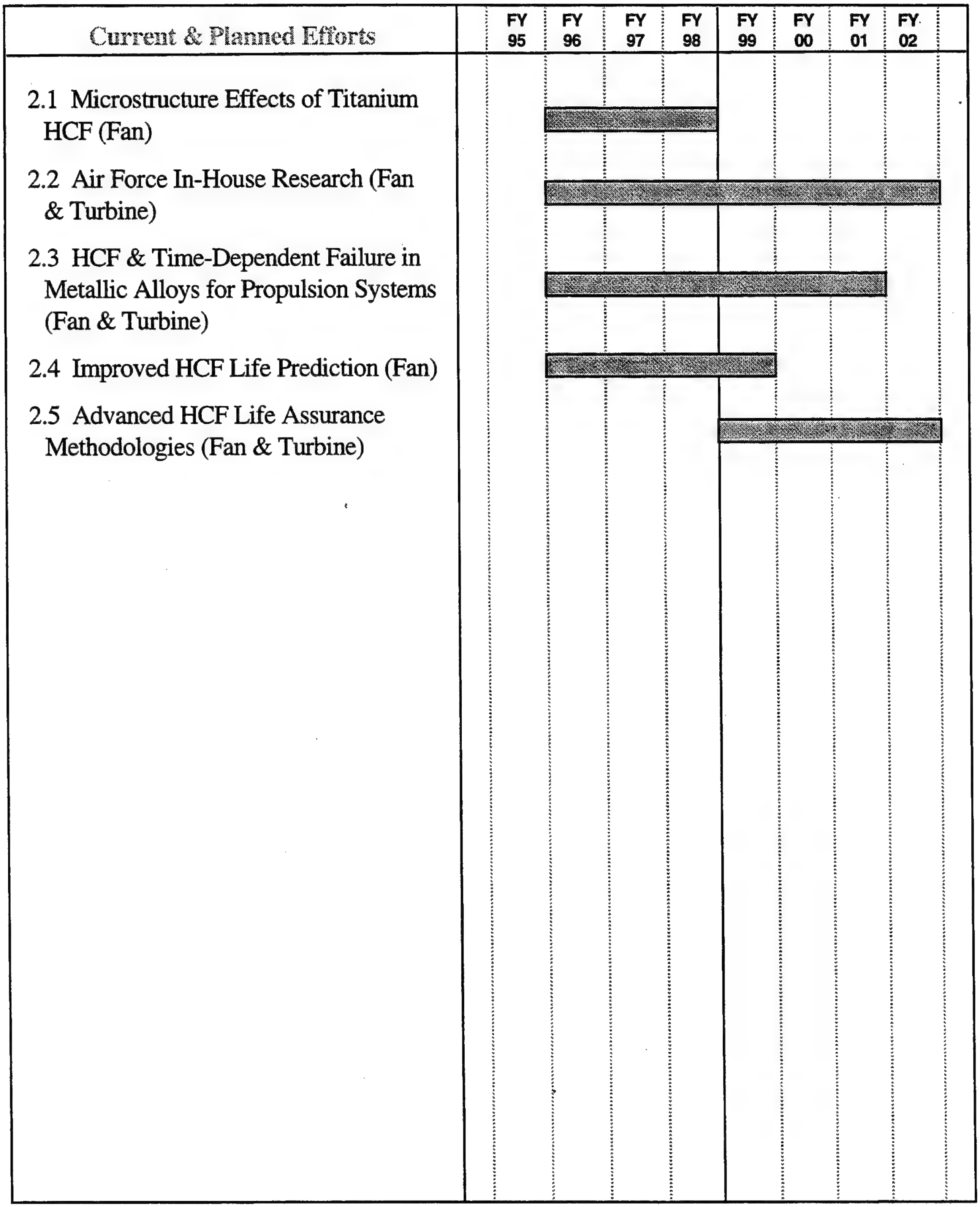
INTRODUCTION

Prior to this research program, no accurate techniques were available to determine the capability of materials subjected to variations in manufacturing, component handling, and usage. Such techniques are needed for accurate life prediction and optimized design to assure damage tolerance. The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Materials Damage Tolerance Research Schedule



2.1 Microstructure Effects of Titanium HCF (Fan)

FY 96-98

<u>**DESCRIPTION / PROGRESS**</u>

The objective of this project is to determine the relationship between mean stresses and high cycle fatigue strength for Ti-6Al-4V by correlating the fatigue crack nucleation process with the cyclic deformation behavior of the alloy for different microstructures and crystallographic texture characteristics.

A workable hypothesis that was investigated was that high mean stress fatigue life sensitivity is associated with cyclic softening of Ti-6Al-4V, which in turn results in the absence of an endurance limit. In addition to establishing such a correlation, the second purpose of the investigation was to study the crystal orientation dependence on, and the microstructural features that affect, the cyclic deformation behavior. The specific factors that control crack nucleation are also being studied. The focus is on the formation of dislocation substructure and the statistical nature of crack formation. Analytical procedures emphasize the use of quantitative physical models that can be used to predict the mean stress sensitivity in this class of titanium alloys. The results should also be useful in the search for the best alloy/process for maximizing fatigue resistance in engineering structures.

The findings of the two aspects of the physical behavior of Ti-6Al-4V that were investigated are described below. These findings contributed to the development of a model to predict of the mean stress sensitivity of Ti-6Al-4V, which is also described below.

Correlation of Cyclic Softening and the Absence of an Endurance Limit. Cyclic strain tests in strain control mode did not reveal significant differences in cyclic deformation behavior between the investigated microstructures (lamellar cross-rolled, bimodal fine uni-rolled, bimodal coarse cross-rolled, bimodal coarse forged, equiaxed coarse cross-rolled, and equiaxed coarse forged). All six microstructures underwent cyclic softening, and the saturation stresses at all strain levels (and hence, cyclic stress-strain curves) were almost identical for all of these microstructures. However, in the initial condition (monotonic stress-strain curve), the differences in saturation stresses were much greater. Unlike S-N (stress-life) curves, little difference was observed between the ε-N (strain-life) curves generated for each of the investigated microstructures, especially at low strains. Also, relatively little scatter was observed for each curve.

Effect of Crystal Orientation and Microstructural Features on Fatigue Behavior. Of the six microstructure/texture combinations investigated, bimodal fine uni-rolled and lamellar cross-rolled displayed superior fatigue properties to the remaining four microstructures (bimodal coarse cross-rolled, bimodal coarse forged, equiaxed coarse cross-rolled, and equiaxed coarse forged). Bimodal fine uni-rolled and lamellar cross-rolled microstructures exhibited Goodman dependence of fatigue strength, while the other four microstructures had anomalous mean stress dependence, with fatigue strength values at intermediate mean stresses being considerably lower than predicted by the Goodman relation.

Analytical Procedures (Models) to Predict Mean Stress Sensitivity. The fatigue data collected in this project have been statistically analyzed to develop a model to predict the effects of microstructure and texture on the fatigue strength of α/β titanium alloys. This effort resulted in a model that allows the

accurate prediction of fatigue curves for titanium alloys from microstructure and texture characteristics at different R ratios ($\sigma_{min}/\sigma_{max}$). Separate models have been developed for low cycle and high cycle fatigue regimes, and for three ranges of R: R<0 (tensile-compressive loading), $0 \le R \le 0.5$ (tensile-tensile loading) and $0.5 < R \le 0.7$ (creep-fatigue interaction). For each of these regimes, fatigue strength is calculated as a function of alpha grain size d_α, transformed beta volume fraction v_β, texture orientation parallel to test direction X_α, ultimate tensile strength U, and ductility (reduction of area) e_f.

Figure 8 demonstrates how the model (presented with solid curves) fits actual data points for three different microstructures at R=0.1. The following equations were used to construct these curves:

1. LCF regime, $0 \le R \le 0.5$

$$\sigma_L = 101.457 + 5.565\, v_\beta + 21.562\sqrt{d_\alpha} - 44.629\, e_f - 1.077\, X_\alpha - 6.227\sqrt{d_\alpha}\,\log N - 0.21U\,R$$

2. HCF regime, $0 \le R \le 0.5$

$$\sigma_H = 91.859 + 10.427\, v_\beta - 8.529\sqrt{d_\alpha} - 5.208\log N - (10.684/\sqrt{d_\alpha} + 0.164U)\,R$$

where: d_α = alpha grain size, µm
v_β = transformed beta volume fraction
X_α = texture orientation parallel to test direction (x random)
U = ultimate tensile strength (Ksi)
e_f = ductility (reduction of area)
N = number of cycles
R = stress ratio ($\sigma_{min}/\sigma_{max}$)

The model was tested on the investigated microstructures, and accurately predicted the fatigue strength of α/β titanium alloys for the following range of parameters:

d_α = 3-16 µm
v_β = 0.15-0.80
X_α = 4-13
U = 138-173 Ksi
e_f = 0.30-0.55

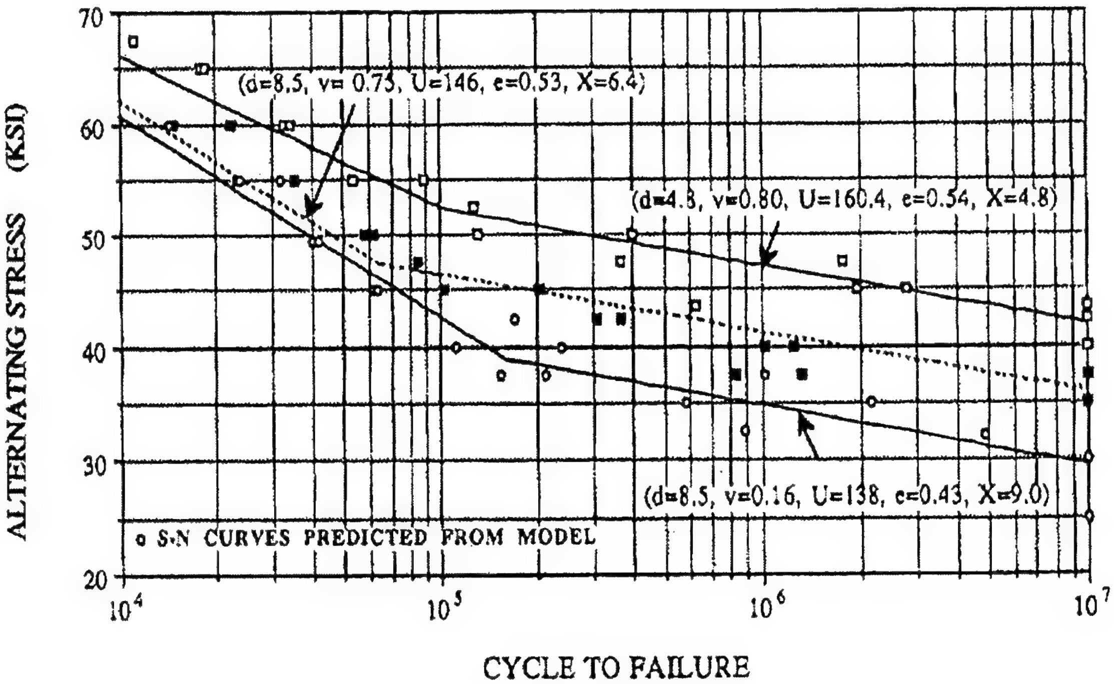


FIGURE 8. S-N Input Data and Fatigue Strength Model Results for Bimodal Fine Uni-Rolled, Bimodal Forged, and Equiaxed Forged Microstructures (Top to Bottom) at R=0.1

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2.2 Air Force In-House Research (Fan & Turbine)

FY 96-02

DESCRIPTION / PROGRESS

The objectives of this program are: (1) to conduct breakout research on titanium and nickel-base superalloys; (2) to explore high cycle fatigue related damage mechanisms, including the determination of the relative significance of specific damage mechanisms and the identification of specific areas requiring a concentrated research and development effort for incorporation into the HCF design system; (3) to develop innovative test techniques and modeling concepts to guide the industry research program; and (4) to conduct research and evaluation to demonstrate and validate damage tolerance design methodologies for HCF.

During the past year, progress has been made in all areas. The following paragraphs highlight specific accomplishments with regard to the approaches being taken in this project.

- ***Material Behavior for Modeling.*** Testing has been accomplished to generate valid data for modeling the damage mechanisms associated with high cycle fatigue interaction with low cycle fatigue (LCF), fretting fatigue, and foreign object damage (FOD). Data have also been generated to characterize crack growth / arrest in laser shock peened fan blade specimens subjected to HCF loading.

  - *High Cycle Fatigue / Low Cycle Fatigue Interaction.* A study was performed to determine the amount of constant amplitude LCF precycling that would be required to lower the HCF capability of Ti-6Al-4V. It has been demonstrated that LCF precycling to 50% of the material LCF life has no significant effect on HCF life, and precycling to 75% of LCF life has a small effect on HCF life. Additional testing will be accomplished to determine the amount of LCF precycling necessary to impact HCF life. HCF/LCF spectrum testing will also be accomplished to determine load interaction effects. Additionally, frequency effects will be elucidated during the next year. The accurate modeling of load interaction effects is necessary for accurate life prediction and optimized design.

  - *HCF Fretting Fatigue.* Three studies and a modeling effort on fretting fatigue are being accomplished in this program.

    - In the first study, test specimens are axially loaded with both HCF and LCF cycling, while having a fretting block normal to the specimen surface. Various fretting block configurations (flat surface, cylindrical surface, flat with tapered edges) are being investigated to elucidate the first-order fretting fatigue parameters for fretting fatigue modeling.

    - In the second study, the effects of contact stress, stress ratio, and fretting pad contact area on fretting fatigue life are being investigated. Preliminary tests have provided inconclusive results. Additional testing will be performed in the next year.

    - In the third study, which started recently, the effects of coatings on the fretting fatigue life of Ti-6Al-4V are being investigated. No results have been attained as yet.

➢ *HCF and Foreign Object Damage.* Three studies are being performed in this area.

- The first study is focused on notches, investigating the effects of notch radius, notch depth, specimen geometry, and load history on crack nucleation life. Preliminary notch fatigue data with a stress concentration factor of $K_t = 2.7$ indicate that when accounting for the plastic redistribution of stresses (under constant amplitude or LCF/HCF loading), and the biaxial stress state, the data generally agree with unnotched data. Preliminary load history tests show LCF precycling to 10% of LCF life (R=0.1 at 10^5 cycles) reduces the HCF strength (R=0.8 at 10^7 cycles) by approximately 10%.

- The second study is an investigation of the effect of ballistic particle impact damage on HCF life. In this study, fan blade specimens are impacted with glass balls (1 mm diameter; 1,000 ft/sec; 0°, 15°, 30° and 45° impact angle), then fatigue cycled in pure HCF (constant amplitude), and step tested to determine the mean and alternating stresses for a lifetime of 10^7 cycles. Preliminary results show the largest decrease in fatigue strength with an impact angle of 30°. Further experiments involve testing with 2mm diameter spheres and thinner leading edge geometries.

- In the third study, the effect of foreign object damage (FOD) on the high cycle fatigue life (10^7 cycles) of fan blades is being investigated. Two types of FOD damage (glass bead impacts and quasi-static chisel indentation, both at radii of 1mm and 2.5mm) are being examined. The preliminary work indicates that similar fatigue lives are produced when the plastic damage zone sizes from the two techniques are similar.

➢ *Crack Growth / Arrest in Laser Shock Peened Fan Blades.* The Laser Shock Peening (LSP) process imparts compressive residual stresses on the surface of metallic components in much the same way that conventional shot peening does, only it imparts the stresses to a deeper level. This zone of residual stresses counters bulk stresses imparted on the component in a superpository manner. Both notch fatigue and the subcritical crack growth behavior of Laser Shock Peened (LSP'd) Ti-6Al-4V fan blade leading edge crack growth specimens (Fig. 9) were examined in four-point bending and compared to unprocessed material. The LSP'd specimens demonstrated much higher notch fatigue capability at low stress ratios, and slightly higher capability at high stress ratios (Fig. 10a). Low stress ratio fatigue crack growth rate testing of specimens which had undergone LSP showed a greater resistance to crack growth than those specimens which were unprocessed (Fig. 10b). High compressive residual stresses imposed by LSP that reduce the locally applied stress were determined to be the mechanism behind the greater resistance. This advantage is not seen at high stress ratios (Fig. 10c). The effective stress intensity factor range, ΔK_{eff}, is used as a correlating factor in the analysis. Metallographic and fractographic analyses were also performed to correlate crack growth behavior. The LSP'd specimens exhibited fracture surface morphologies similar to those seen in fatigue specimens which had undergone compression-compression loading, which is what the ΔK_{eff} analysis shows occurs in the LSP'd samples.

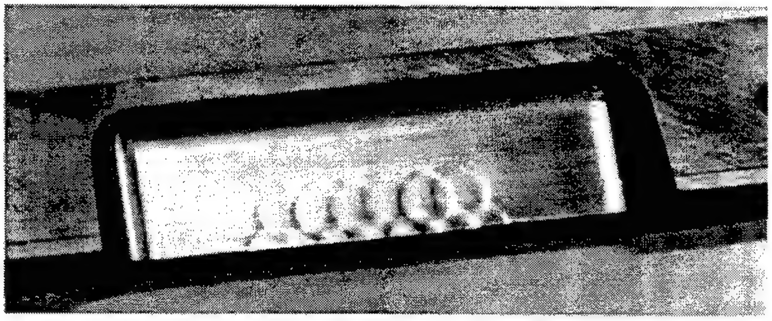
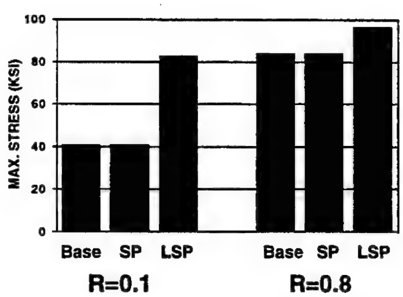
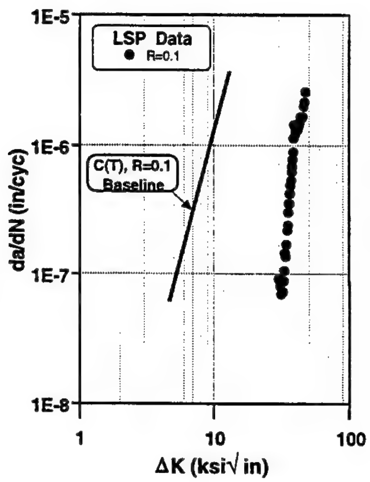


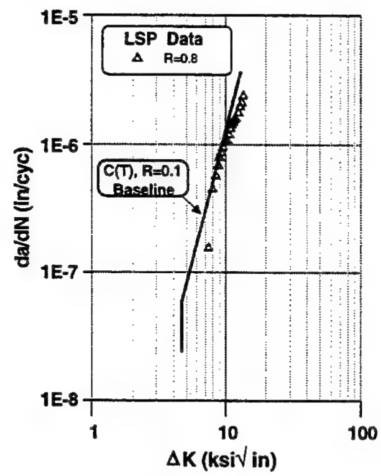
FIGURE 9. Laser Shock Peened Four-Point-Bend Fan Blade Leading Edge Crack Growth Specimen



a) Notched Fatigue Capability of Unpeened (Baseline), Shot Peened, and Laser Shot Peened Specimens



b) LSP Demonstrated Beneficial Effect at Low Stress Ratios

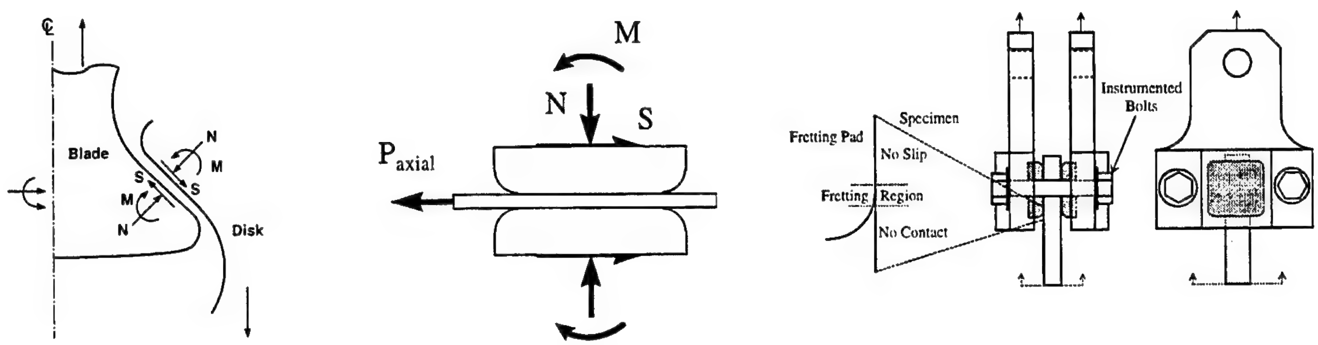


c) LSP Demonstrated Negligible Effect At High Stress Ratios

FIGURE 10. Notched Fatigue and Fatigue Crack Growth Behavior of LSP'd Ti-6Al-4V

❖ ***Crack Threshold Methodology Development.*** Various methods of determining fatigue crack growth threshold stress intensity factor range for $\alpha+\beta$ processed Ti-6Al-4V have been investigated. It has been demonstrated that the determination of ΔK_{th} (crack growth threshold stress intensity factor range) via the constant K_{max} method will show a crack growth threshold $\Delta K_{th} \cong 2$ MPa$\sqrt{m}$ for $K_{max} \leq 25$ MPa$\sqrt{m}$. At max stress intensity values exceeding 25 MPa$\sqrt{m}$, the threshold effect is not present. This phenomenon has not been demonstrated under the case of constant load ratio (R = min stress / max stress). All data to date have been generated with compact tension (CT) specimens which are representative of "long crack" behavior. Investigation of other geometries representative of "small crack" behavior is also necessary and will be conducted in this project.

❖ ***Innovative Test Technique Development.*** A fretting fatigue test apparatus has been developed that imparts stresses similar to those experienced by fan blades in the dovetail region of the blades. Figure 11 schematically shows the stresses that are generated in the dovetail region of a blade – disk attachment. At the contact region (Fig. 11a), both steady-state and temporal normal stresses, shear stresses, torsional stresses and a moment are imparted on the blade / hub interface. These loads are a result of the centrifugal loads due to engine rotation (low cycle fatigue loading – steady-state), and the (temporal) vibrational loads imparted by aerodynamic loading. Although the experimental set-up imparts static loading and a dynamic axial load (Fig. 11b), neither the dynamic normal stresses nor the torsional loads are reproduced in the laboratory. Laboratory loading also does not duplicate the specific load levels, however the general conditions are reproduced, including the generation of "slip" and "no slip" regions (Fig. 11c). A new test and specimen geometry is being designed which is expected to produce test conditions that are even closer to actual service conditions.



a) Stresses at Blade-Disk Interface

b) Stresses in Laboratory Test Specimens

c) Fretting Fatigue Experimental Set-Up

FIGURE 11. In-Service and Experimental Fretting Fatigue Conditions

❖ ***Investigation of Other Damage Mechanisms.*** A study on creep fatigue interaction is being performed to determine the stress ratio (R = min stress / max stress) at which creep has a significant impact. Initial data show that creep occurs at R = 0.75 – 0.8. The effects of ratcheting or cyclic creep are also being investigated for HCF at high values of R. Additionally, an investigation of mechanisms that may relax the beneficial residual compressive stresses imparted by the LSP process will commence this year.

❖ **Analytical Model Development.** During the past year, work has continued on modeling high cycle / low cycle fatigue interaction. For LCF / HCF crack growth, predictions using linear damage summation for blocked cycles with one LCF cycle (R=0.01) followed by 1,000 HCF cycles (R=0.8, $\sigma_{max(HCF)} = \sigma_{max(LCF)}$) per block yielded slightly conservative values of block crack growth rate when compared to test data. Initial results with multiple underloads (10 LCF cycles, R=0.01) followed by 1,000 HCF cycles per block again yielded slightly conservative values of block crack growth rate when compared to test data, however additional testing is required. Additionally, work has begun on a method of modeling the decrease in the fatigue strength for a constant life as a result of fretting fatigue. Modeling of HCF interaction with LCF, fretting and FOD will continue this year.

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2.3 HCF & Time-Dependent Failure in Metallic Alloys for Propulsion Systems (Fan & Turbine)

FY 96-01

DESCRIPTION / PROGRESS

This program is focused on the definition, microstructural characterization, and mechanism-based modeling of the limiting states of damage associated with the onset of high-cycle fatigue failure in titanium and nickel-base alloys for propulsion systems. The goal of this program is to provide quantitative criteria for the evolution of critical states of HCF damage, enabling life-prediction schemes to be formulated for fatigue-critical components of the turbine engine. The specific objectives are as follows:

(1) Perform systematic experimental studies to define crack formation and lower-bound fatigue thresholds for the growth of "small" and “large” cracks at high load ratios, high frequencies, and with superimposed low cycle fatigue loading, in the presence of primary tensile and mixed-mode loading; and analyze the applicability of the threshold stress-intensity factors to characterize crack initiation and growth in engine components subjected to high cycle fatigue.

(2) Define lower-bound fatigue thresholds for crack formation in the presence of notches, fretting, or projectile damage, on surfaces with and without surface treatment (e.g., shot or laser shock peened).

(3) Develop an understanding of the nature of projectile (foreign object) damage and its effect on initiating fatigue crack growth under high cycle fatigue conditions.

(4) Develop new three-dimensional computational modeling tools and detailed parametric analyses to identify the key variables responsible for fretting fatigue damage and failure in engine components; compare model predictions with systematic experiments; identify and optimize microstructural parameters and geometrical factors and surface modification conditions to promote enhanced resistance to fretting fatigue.

(5) Develop mechanistic models of the initiation and early growth of small cracks to characterize their role in HCF failure, with specific emphasis on initiation at microstructural damage sites and on subsequent interaction of the crack with characteristic microstructural barriers; and correlate such models to experimental measurement.

(6) Characterize microstructural damage using new imaging modalities, including both *ex situ* and in particular *in situ* experiments performed in the electron and scanning probe microscopes, as well as thermal/thermoelastic imaging measurements.

During the second year of this research program, considerable progress has been made on all aspects of the program, but especially on the development of the lower-bound threshold concept, both with respect to its measurement and utility to represent a practical lower bound for the onset of small crack growth. Also, significant progress has been made in the modeling and life-prediction methodology of fretting fatigue. Specific accomplishments over the last year are outlined below:

- ***HCF/LCF Interactions.*** Progress has been made in a number of areas supporting HCF/LCF Interactions:
  - *Lower-bound fatigue threshold stress intensity values* have been established for Ti-6Al-4V under representative HCF conditions (high mean stresses, high frequencies) for large (> 5 mm) cracks. These threshold values appear to be independent of frequency, over the range ~20 to 20,000 Hz, and are found to be lower than the limiting conditions for the onset of small (~ 45-1,000 μm) crack growth from naturally-initiated flaws (Fig. 12).
  - A COD (crack opening displacement) gage capable of monitoring crack lengths in nickel-base alloys at 1 kHz and at temperatures up to 1,100°C has been developed and successfully demonstrated.
  - Theoretical solutions for the factors (crack-tip opening/shear displacements) controlling the growth of small (Stage I) fatigue cracks under monotonic and cyclic loads have been developed, as a basis of a comprehensive mechanics description of small-crack growth.

- ***Notches and Foreign Impact Damage.*** Foreign object damage, simulated by hardened steel sphere impacts at 200-300 m/s, was observed to provide preferential sites for the initiation of small fatigue cracks in Ti-6Al-4V, such that smooth-bar fatigue lives were many orders of magnitude shorter than in un-impacted samples. Subsequent small-crack growth from the damage sites was found to occur at rates considerably faster than large cracks subjected to the same applied stress intensity ΔK level (Fig. 12). Lower-bound large crack threshold values were again found to represent the limiting conditions for the onset of small crack growth from the damage sites.

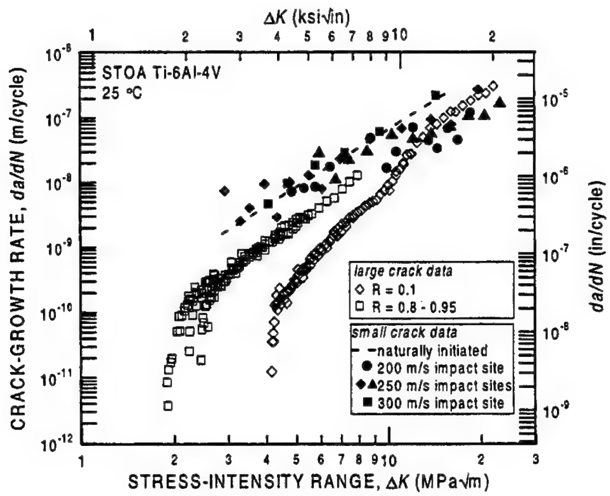

FIGURE 12. Fatigue-crack propagation results for naturally-initiated small (~45-1,000 μm) surface cracks in Ti-6Al-4V at R = 0.1 (line) and for small cracks emanating from a variety of FOD impact sites (closed symbols) in the solution treated and overaged Ti-6Al-4V alloy, as compared to through-thickness, large cracks (>5 mm) at R = 0.1 and 0.8-0.95

❖ ***Fretting Fatigue.*** Progress has been made in a number of areas supporting fretting fatigue:

- ➢ A new life prediction methodology for fretting fatigue, termed the "Crack Analogue Method," has been developed and applied to geometries of relevance to the aircraft jet engine components (Fig. 13).
- ➢ A new three-dimensional finite-element method for simulating cyclic frictional contact problems, termed the "Contact Fatigue Simulator," has been developed to simulate sharp and rounded edge fretting fatigue contacts (Fig. 13).
- ➢ A new experimental set up, which is capable of quantitatively measuring *in situ* all the parameters of interest in assessing fretting fatigue damage, has been developed and calibrated. Experiments have been initiated on titanium alloys.
- ➢ A new theoretical model for the fretting of coated metal surfaces has been developed which specifically addresses the role of plastic deformation of the metal substrate.

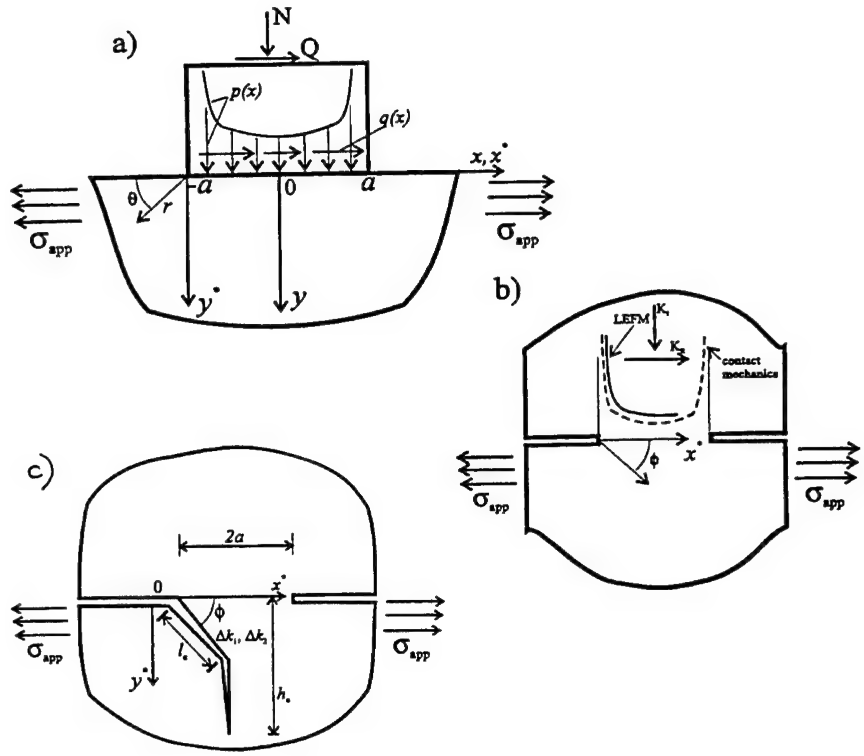

FIGURE 13. (a) A schematic representation of the fretting contact between a two-dimensional rectangular punch and a substrate. (b) Crack analogue of (a) showing the double edge cracked plate specimen, which is subjected to Mode I and Mode II stress intensity factors K_I and K_{II}. (c) Analysis of cracking patterns in fretting fatigue using the crack analogue model. A small surface crack initiates at an angle ϕ_{in} to the contact surface and advances into the substrate over the distance l_c. It then reorients itself normal to the external cyclic stresses $\Delta\sigma_{app}$ and penetrates the substrate over a distance h_c, at which point catastrophic failure initiates.

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2.4 Improved HCF Life Prediction (Fan)

FY 96-99

DESCRIPTION / PROGRESS

The focus of this program is on the development of damage tolerant design processes for gas turbine engines that substantially reduce the potential occurrence of high cycle fatigue failures in titanium (fan) structures. Specific objectives for this program are: (1) to characterize in-service damage associated with high-cycle fatigue loading of titanium fan blades; (2) to develop techniques to generate damage states in the laboratory that are representative of in-service damage; (3) to model the nucleation and progression of damage in titanium fan blades; and (4) to develop an improved damage tolerant life prediction and design methodology for turbine engine rotating structures subjected to high cycle fatigue (HCF) and combined high and low cycle fatigue (HCF/LCF) loadings.

This program is being accomplished through the development of a better understanding of the three primary damage mechanisms experienced in the fan section, and the transitioning of that understanding into the development of improved damage tolerance life prediction methodologies. All experimental studies are being performed on $\alpha+\beta$ processed Ti-6Al-4V forged plate, specifically produced to provide a representative titanium alloy with consistent properties that would minimize data scatter due to material inhomogeneities. Specifically, this program is being performed through the accomplishment of research in the following areas:

- *HCF/LCF Interactions* research is aimed at developing a better understanding of the fatigue and crack growth damage accumulation processes due to the load interactions generated in LCF/HCF loading. This includes the study of fatigue crack threshold behavior for both pristine and LCF damaged material (with various surface treatments), as well as the development of baseline material data for comparison with other damage modes.
- *Foreign Object Damage* research is aimed at developing a better understanding of the occurrence and levels of FOD in different sections of turbine engines and characterizing of the relevant parameters for modeling FOD damage progression. Techniques for reproducing damage representative of in-service FOD are being investigated and specimens containing laboratory-induced FOD will be tested to characterize the effects of FOD.
- *Fretting Fatigue* research is aimed at developing a better understanding of the occurrence and levels of fretting fatigue damage at the fan blade root / disk hub interface. Techniques for reproducing damage representative of in-service fretting fatigue are being investigated and specimens containing laboratory-induced fretting and fretting fatigue damage will be tested to characterize the effects of fretting fatigue on the HCF behavior. Criteria for the initiation and propagation of cracks under fatigue in contact regions will be developed.
- *Damage Tolerant Life Prediction Methodologies* research is aimed at utilizing data generated to characterize the damage mechanisms described above to develop new, more accurate methods of modeling the initiation and progression of damage in titanium fan blades. Existing methodologies will be modified where possible, and new methodologies will be developed as necessary. Validation of life prediction methodologies will be accomplished through the comparison of predictions to experimental and service data.

During the past year, progress has been made in several areas. Progress in the development of damage tolerant life prediction methodologies is reported in the appropriate damage mechanism sections.

- ***High Cycle Fatigue / Low Cycle Fatigue Interaction.*** Several efforts are being performed to investigate HCF/LCF interaction, HCF/LCF threshold crack growth behavior, and other related phenomena. Specific areas of progress are described below:

  - The modified-Goodman behavior (constant amplitude alternating stress capability as a function of mean stress) of the Ti-6Al-4V is being characterized. Notched and unnotched, stress free (stress relieved plus chem milled) and shot peened specimens (two intensities) are being characterized. Testing is being accomplished at several different frequencies to quantify frequency effects, and at lifetimes of 10^6, 10^7, 10^8 and 10^9 cycles. Early concern has been expressed about the surface condition of the stress relieved plus chem milled specimens. Detailed scanning electron microscopy and metallographic examination has been completed. It was concluded that this was a problem with a few of the first batch of specimens. A 100% visual inspection for orange/gold stain has been added to the machining specification to assure that it will not happen in future machining.

  - HCF/LCF interaction experiments focused on near-threshold fatigue crack growth are being performed. Periodic LCF unloads from high stress ratio HCF cycling (1 LCF cycle per 10^5 or 10^6 HCF cycles) were found to cause 3x accelerations in near-threshold fatigue crack growth rates compared to the predictions of linear damage rules. High resolution, near-tip measurements and analyses of the above experiments indicated that appreciable crack closure occurred in the near-threshold HCF cycles, even at high R (min stress / max stress ~ 0.85), prior to LCF unloads. Comparisons of crack-tip displacement fields before and after LCF unloads revealed significant increases in CTOD (crack tip opening displacement) and crack-tip shear strain ranges immediately following the LCF cycle, which are consistent with accelerations in fatigue crack growth rate. Ongoing experiments are investigating these phenomena in more detail, including the transient nature of the crack closure response.

  - A proposed method for evaluating and modeling potential mechanically-small crack effects in the program Ti-6-4 alloy under HCF conditions was developed. The method is based on an $(a + a_o)$ effective crack size formulation similar to that proposed by El Haddad and Tanaka, where a_o is a function of the smooth specimen endurance limit ($\Delta\sigma_e$) and the long crack stress intensity factor threshold (ΔK_{th}). The effective crack size term can be implemented either in crack-size dependent modifications to the crack driving force, ΔK, or in crack-size dependent modifications to the threshold, ΔK_{th}. Diagnostic small crack experiments are being planned to evaluate the above model and determine if mechanically small crack effects are significant for HCF life methods.

  - An effort investigating multiaxial fatigue behavior has recently begun, however no conclusions can be made at this time. This information will provide critical information for modeling fatigue initiation and propagation under multiaxial stress states that occur in fielded hardware, including those in regions where fretting fatigue is encountered.

- ***Foreign Object Damage.*** The characterization of in-service FOD, and several methods of producing laboratory-induced FOD representative of in-service FOD are being investigated. Specific areas of progress are:

  - A total of 51 fan blades, all from either the first, second, or third stage fans from F100 engines were examined to characterize typical in-service FOD damage. In general, the FOD consisted

of dents, tears, and notches, primarily to the leading edge of the blade; in 40 cases the damage was on the leading edge and in two cases the damage was on the trailing edge of the blade. In two cases, the leading edge damage consisted of FOD that had previously been blended and returned to service. Notch depth and root radius was recorded for all FOD sites. This data will be used both in life prediction modeling and in setting requirements for laboratory-induced FOD.

- Different methods of inducing FOD in the laboratory have been investigated. Specifically, ballistic FOD induced by glass beads and shot, and chisel indent methods induced via quasi-static and various dynamic techniques have been investigated. The critical parameters for a study of the different quasi-static and dynamic chisel indent methods have been defined. Results will be compared to ballistic and in-service FOD to identify a standard method of inducing FOD in the laboratory.

- Literature relevant to the effects of geometric stress concentration on the initiation, propagation and arrest of fatigue cracks at notches in the HCF regime was used to formulate a "worst case notch" model to predict the fatigue threshold stress for FOD-type notches. To implement the "worst case notch" model, stress intensity factor (SIF) solutions have been developed for cracks at notches subjected to arbitrary stressing based on the weight function method. This method enables SIFs to be calculated from stress distributions obtained in the crack-free component. Approximate weight functions for cracks at notches were generated from the SIF solution for a crack at the root of a semi-circular notch. This weight function solution was incorporated into a computer program that calculates fatigue threshold stresses for cracks at notches using the parametric expressions for the stress concentration factors, k_t, and the stress distributions at notches previously derived in this task. This computer program was used to demonstrate that the "worst case notch" concept applies to Ti-6-4 material – that is, the fracture mechanics calculations demonstrated a threshold stress that becomes independent of notch severity for high k_t values. This model is currently being used to further explore the possible dependence of the threshold stress on geometric variables (notch depth and root radius), loading variables (loading mode and R-ratio), as well as material properties ($\Delta\sigma_e$ and ΔK_{th}).

- ***Fretting Fatigue.*** The characterization of in-service fretting fatigue damage and the development of methods to produce fretting fatigue damage representative of in-service fretting fatigue are being investigated. Specific areas of progress are:

  - A design of experiments based study on pre-fretting (fretting without the fatigue) was initiated to explore the range of fretting test parameters (e.g., bearing stress and slip distance). The results of these tests will define those parameters that produce fretting damage similar to that experienced in fielded hardware.

  - Pseudo-analytical techniques for calculation of fretting fatigue contact pressure distribution have been developed and compared to existing analytical expressions for reduced cases. The technique has been extended to examine the effect of moments that might cause rocking of the fretting pad in the experimental set-up. The finite element procedures for calculation of the mixed mode stress intensity factors induced by fretting loading of surface breaking cracks have also been developed. Again, the procedure has been verified through comparison to analytical solutions for reduced cases. Finite element models have also been developed for an experimental configuration that includes a nominally flat fretting pad. The comparison between the finite element and pseudo-analytical results is promising, indicating that it will be possible to calculate stress intensity factors for cracks near the nominally flat contacts using the finite element modeling. Additionally, calculations have been made to investigate the interaction

between high and low cycle loading in fretting fatigue. This will be investigated in greater detail during the next year.

- For the geometry investigated in this effort (teardrop contact pad), optical examination of the fretting contacts showed that damage nucleation leading to failure occurred both near the edge of contact as well as near the center of contact for various specimens. Examination of failed specimens has revealed embryonic cracks at the edge of contact that did not propagate to failure. Additionally, cracks propagating parallel to the fretting surface were readily observed which eventually would have lead to flaking. Two-dimensional finite element modeling of the laboratory fretting fatigue specimens is being performed to determine the stress conditions throughout the specimens. For the teardrop contact pad, the maximum principal stress (the stress considered to dominate the fretting fatigue crack nucleation process) occurs directly below the fretting contact and extends deeply into the specimen.
- Methods of imparting normal and shear stresses that more accurately reproduce the in-service loading conditions are being investigated. Various contact geometries and methods of imparting alternating normal and shear stresses are being investigated.

PARTICIPATING ORGANIZATIONS

University of Dayton Research Institute, General Electric Aircraft Engines, Pratt & Whitney, Rolls Royce Allison, AlliedSignal Engines, Southwest Research Institute, Purdue University, United Technologies Research Center, SRI International, and the University of Illinois

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2.5 Advanced HCF Life Assurance Methodologies (Fan & Turbine)

FY 99-02

DESCRIPTION / PROGRESS

This program is a follow-on effort to Effort 2.4, "Improved HCF Life Prediction." This program is focused on the extension and validation of the technologies developed in the earlier effort to other titanium alloys for use in the fan section, as well as to single crystal nickel-base superalloys for use in the turbine section. The objectives of this program are: (1) to extend the understanding of damage mechanisms in $\alpha+\beta$ processed Ti-6Al-4V blades and disks to other titanium alloys with varying microstructures, (2) to develop a better understanding of the underlying damage mechanisms to which single crystal nickel-base superalloy blades and disks are subjected, and (3) to extend and validate the damage tolerant life prediction and design methodologies developed for $\alpha+\beta$ processed Ti-6Al-4V to other titanium alloys and to single crystal nickel-base superalloys.

A comprehensive database of test results will be developed which describes all aspects of material HCF behavior for β-processed Ti-17 titanium and PWA 1484 single-crystal nickel-base superalloy. The damage states that increase the potential for HCF failures will then be defined. Finally, improved test methods, improved analytical approaches, and total life prediction software for titanium and single crystal superalloy, will be developed.

This contract is currently being negotiated. The projected contract award date is December 1998.

PARTICIPATING ORGANIZATIONS

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3.0 INSTRUMENTATION

BACKGROUND

The Instrumentation Action Team (Instrumentation AT) has the responsibility of fostering collaboration between individual HCF instrumentation efforts with the overall goal of combining with the Forced Response and Component Analysis ATs to better determine alternating stresses to within 20%. The Instrumentation AT provides technical coordination and communication between active participants involved in HCF measurement, sensor, data processing, and engine health monitoring technologies. Technical workshops have been organized on at least an annual basis and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Instrumentation AT members meet as required (estimated quarterly) to review technical activities, develop specific goals for instrumentation and engine health monitoring programs, and coordinate with the TPT and IAP. The Chairman (or Co-Chair) of the Instrumentation AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in instrumentation technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

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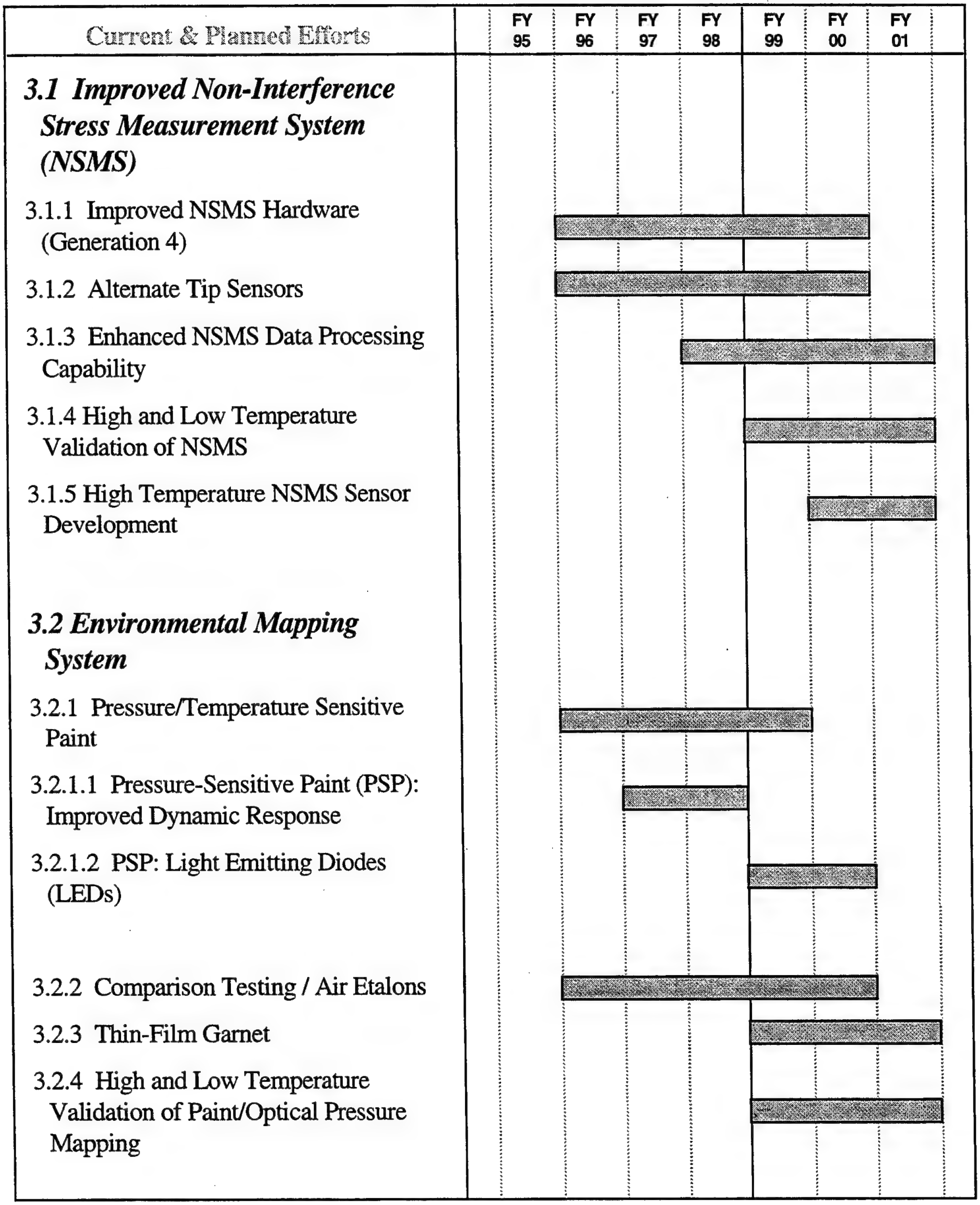
INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Instrumentation Schedule



Instrumentation Schedule *(Cont.)*

Current & Planned Efforts	FY 95	FY 96	FY 97	FY 98	FY 99	FY 00	FY 01
3.3. Improved Conventional Sensors							
3.3.1 Non-optical NSMS Sensor Development (Eddy Current)							
3.3.2 Development of Long-Life, Less Intrusive Devices							
3.3.2.1 Advanced Thin-Film Dynamic Gages							
3.3.2.2 Advanced High-Temperature Thin-Film Dynamic Gages							
3.3.2.3 Spin Pit Validation of Strain Gages							
3.3.2.4 Spin Pit Validation of High Temperature Strain Gages							

3.1 *Improved Non-Interference Stress Measurement System (NSMS)*

To date, prediction of aerodynamic forcing functions has been difficult or impossible due to lack of Computational Fluid Dynamics (CFD) fidelity, structural modeling accuracy, instrumentation effects, and insufficient characterization of instrumentation installation effects. The purpose of the projects described below is to develop an advanced generation NSMS (Fig. 14) capable of detecting simultaneous integral-order modes with a 5X improvement in accuracy, and to provide the ability to accurately convert the measured tip deflection to a dynamic stress map.

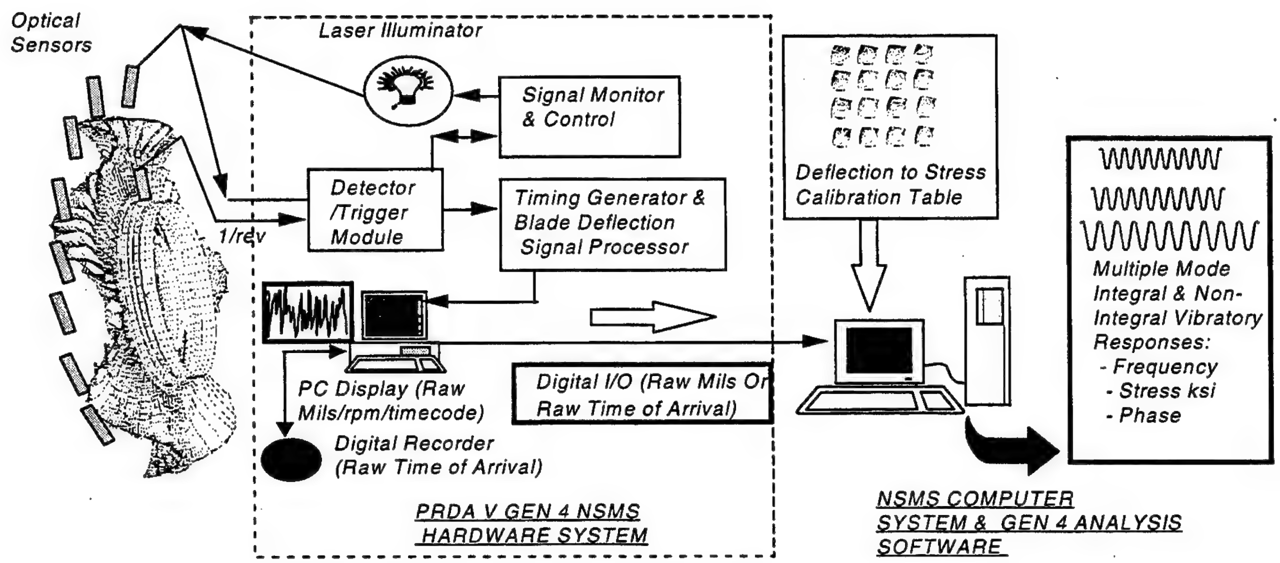


FIGURE 14. Next-Generation NSMS Overview

3.1.1 Improved NSMS Hardware (Generation 4)

FY 96-00

DESCRIPTION / PROGRESS

Overall, preliminary designs have been completed and prototyping and bench testing of major subsystems are well underway. The custom-designed chassis for the Blade Timing Generator (BTG) has been procured along with prototype printed circuit boards for the Master Clock and Timer cards. Assembly and checkout of these are proceeding. The PC (personal computer) and Digital Signal Processor cards for the Blade Deflection Signal Processor (BDSP) have been procured. User inputs for the Graphical User Interface are being defined. Design and layout of the Detector/Laser board with remote control interface have been completed and software for the system controller is being written. An enhanced trigger circuit design has been prototyped and checked out using optical probe signals from an engine test that were recorded on FM Wideband tape. The vendor has been selected for development of assembly/fabrication techniques for the multi-lens 700 F optical line probe. A lower temperature version of the multi-lens line probe is being used extensively in current F119 ISR (Initial Service Release) and other development engines.

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3.1.2 Alternate Tip Sensors

FY 96-00

DESCRIPTION / PROGRESS

As part of the Fourth Generation NSMS development effort, a study has been made of alternate (i.e., non-optical) NSMS sensors. The motivation for this study arises principally from problems associated with applying optical sensors, namely installation complexity and susceptibility, to optical contamination. These problems are of paramount importance in flight test and engine health monitoring applications (but are of less concern in ground based engine testing). A sensor capability specification was prepared with input from the members of the Fourth Generation NSMS design team. This sensor specification defines the requisite characteristics of sensors to be used for engine health monitoring and Third and Fourth Generation NSMS applications. This sensor specification was used as a basis for evaluating the suitability of alternative sensor technologies for Fourth Generation NSMS applications. The alternative sensor technologies identified to date, while meeting the benchmark characteristics of engine health monitoring and Third Generation NSMS applications, do not possess either the requisite bandwidth or spatial resolution required for Fourth Generation NSMS applications.

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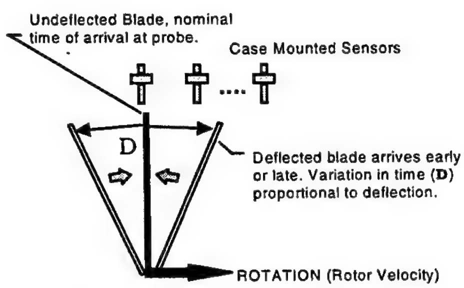
3.1.3 Enhanced NSMS Data Processing Capability

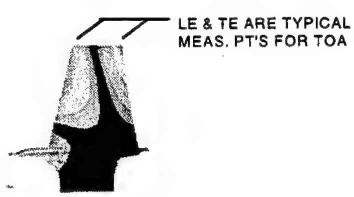
FY 98-01

DESCRIPTION / PROGRESS

Algorithms and software will be developed for processing blade-tip deflection information produced by the Generation 4 NSMS Front-End Hardware System, which is currently in development (Fig. 15). The selected host computer will be fully compatible with the Generation 4 NSMS Front-End System and will comply with government/industry processor guidelines. The Processing System will receive data in real time from the Front-End Hardware System or from archived data. Processing algorithms will characterize individual blade and bladed disk system vibration modes at multiple, simultaneously occurring, integral and nonintegral frequencies. The system will process data from multiple line and/or spot probes arranged in various configurations on multiple engine stages, and provide on-line real time analysis capability at an update rate of at least twice a second. Time and frequency domain analysis defining blade-tip vibration amplitudes, phases, frequencies, damping, and blade untwist in a variety of display formats will be provided. Data will be formatted to interface with blade-tip-deflection to stress conversion algorithms. Fully interactive software tools will be provided to facilitate system setup, calibration, and analysis with simultaneous processes displayed on screen windows. Thereafter, advanced algorithms and Generation 5 NSMS will be researched and developed.



BLADE DEFLECTION OBTAINED FROM TOA MEASUREMENTS



BLADE MODE SHAPE: Depicts Spatial Distribution of Lines of Constant Deflection Through out the Blade. Each Vibratory Response has Unique Spatial Characteristics and Deflection to Stress Amplitude Ratio (ksi / mil)

FUNDAMENTAL MEASUREMENT:
VARIATION IN TIME OF ARRIVAL (TOA) IS PROPORTIONAL TO OVERALL BLADE DEFLECTION
- Sensors case mounted and non -contacting
- High speed Clock (20 nano-sec's) and Counters time blade arrivals & Time of Revolution

ANALYSIS:
OVERALL BLADE DEFLECTIONS ARE ANALYZED TO DETERMINE VIBRATORY COMPONENTS:
- For each vibratory component caluclate :
  .. Deflection amplitude, phase, order (freq), damping
- Responses synchronous with engine rotation (integral) & non-synchronous (non-integral) require different analyses and quantities of probes

STRESS CALIBRATION:
ACCURATE DEFLECTION TO STRESS AMPLITUDE DETERMINATION REQUIRES:
- Accurately known measurement location on blade
  .. Optical Line Probes & beams provide most accurate location
  .. Optical & Non-optical Spot sensors rely on predictions for location
- Accurate deflection measurements of component responses
  .. More probes (more samples) yield more accurate results
  .. Assumptions in Analysis Algorithms
  .. Sensor and Signal Conditioning Sensitiviy
- Accurate Vibratory Mode Shapes
  .. Finite Modeling
  .. Holography (Lab)
- Deflection to Stress Amplitude Calibration by:
  .. Finite Modeling
  .. Shaker Testing (optical telescope & SG's)
  .. Spin Pit Testing (correlation with SG's)
  .. Engine Testing (correlation with SG's)

CURRENT STATE OF THE ART SYSTEMS ARE CAPABLE OF MEASURING MULTIPLE OCCURRING SYNCHRONOUS & NON SYNCHRONOUS VIBRATORY MODES YIELDING 3 TO 5 MILS P-P COMPONENT DEFLECTIONS. GEN 4 SYSTEMS WILL BE CAPABLE OF MEASUREMENTS DOWN TO 1 MIL OR LESS.

FIGURE 15. Rotating Blade Dynamic Stress Determination by NSMS

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3.1.4 High and Low Temperature Validation of NSMS

FY 99-01

DESCRIPTION / PROGRESS

The newly developed Generation 4 NSMS Front-End Hardware and probes will be utilized and transitioned to a room-temperature spin rig validation test. Based on the results of these tests, probe and system accuracy levels will be determined. The need for system modifications depends on the level of accuracy demonstrated. After completion of the data reduction for the room-temperature tests, a test plan incorporating the lessons learned for these low temperature tests will be developed to integrate the Generation 4 system with the high temperature probes and the enhanced NSMS Data Processing Algorithms. This integrated system will then be validated through a series of controlled heated spin pit tests.

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3.1.5 High Temperature NSMS Sensor Development

FY 00-01

DESCRIPTION / PROGRESS

NSMS sensors do not currently have the high temperature capability necessary to adequately monitor high pressure turbine (HPT) blades in the engine environment. The purpose of the project is to develop high temperature probes to interface with the existing Generation 4 NSMS signal processing hardware. Light probes for ground test applications and Eddy Current probes for Engine Health Monitoring will be investigated. A major emphasis of this project will be balancing the increased temperature capability with sensor life and accuracy.

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3.2 *Environmental Mapping System*

To date, prediction of aerodynamic forcing functions has been difficult or impossible due to lack of Computational Fluid Dynamics (CFD) fidelity, structural modeling accuracy, instrumentation effects, and insufficient characterization of instrumentation installation effects. The purpose of the projects described below is to develop an optical pressure and temperature measurement system to non-intrusively measure the dynamic pressure and temperature distribution over the surface of the blade.

3.2.1 Pressure/Temperature Sensitive Paint (PSP/TSP)

FY 96-99

DESCRIPTION / PROGRESS

For application demonstration, the PSPs developed under this effort were applied to a full-scale state-of-the-art transonic compressor. The primary objective of this test was to obtain quantitative pressure measurements from the suction surface of the first-stage rotor. The following paragraphs describe the test article and test set up. At the aerodynamic design point, the relative Mach number was supersonic over 75% of the blade span. The design speed of the rotor is 13,288 rpm. Peak efficiency at 85% Nc speed was the overall peak efficiency of the compressor. Therefore, the first-stage rotor was at least

moderately loaded for the peak-efficiency condition used in this demonstration. Figure 16 depicts the area of the blade where temperature and pressure data were acquired from the rotor described above at the 85% corrected speed, peak-efficiency condition. The approximate dimensions of the viewable area of the blade where data were acquired are from 0 to 52% chord at the tip and from 62 to 100% span at the leading edge. The spatial resolution obtained was 1.2 mm in the direction of rotation and 0.4 mm radially; about 20,500 adjacent data points were acquired over the measurement area. An average of fifteen TSP and fifteen PSP images obtained at the 85% Nc, peak-efficiency condition were used to determine the surface temperature and pressure. The TSP was used to directly to correct the PSP. The measurement uncertainty for the TSP was a ±9 °C and ~ ±2.8 psi for the PSP over the measurement area. The unacceptable high uncertainties were due to a hardware problem that affected the measurement error of the camera. A new camera has been identified for future tests that will offer an improvement of about tenfold in measurement error.

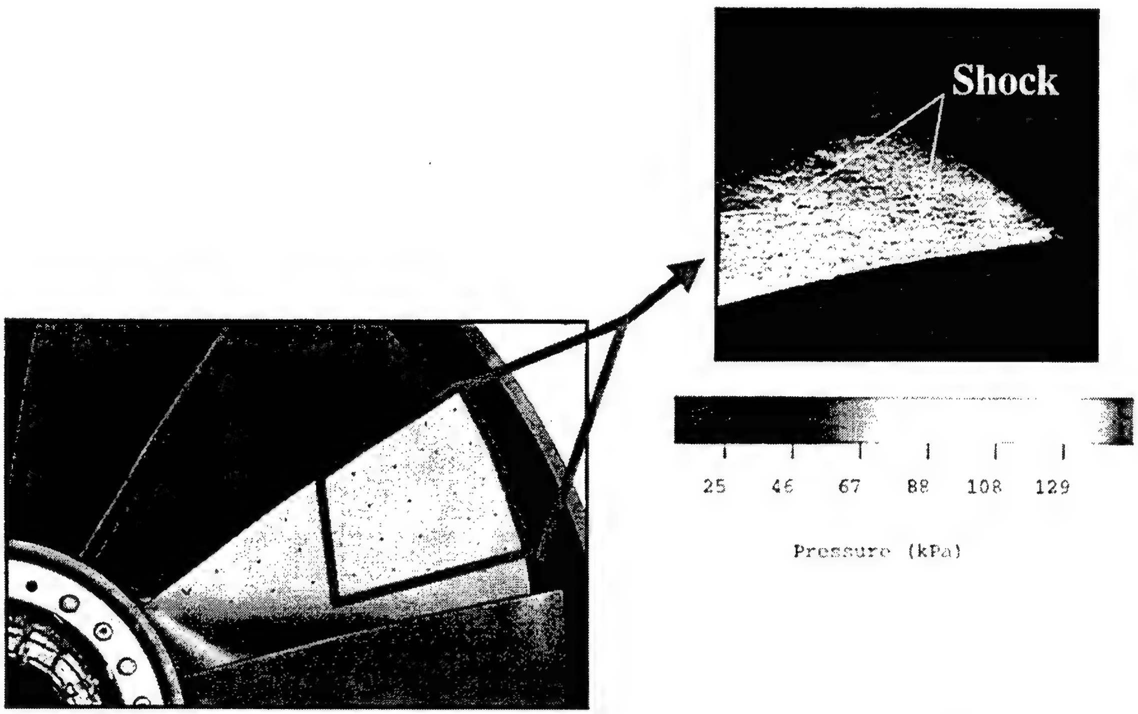

FIGURE 16. Pressure Sensitive Paint (PSP) Data Acquired from State-of-the-Art Rotor at 85% Nc, Peak-Efficiency Condition

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3.2.1.1 Pressure Sensitive Paint (PSP): Improved Dynamic Response

FY 97-98

DESCRIPTION / PROGRESS

Characterizing the transient response of PSPs to unsteady pressure flows is a critical aspect in understanding HCF events. A group led by B. Carroll previously developed an apparatus capable of delivering a step change in pressure, and reported response times for proprietary PSP formulations tested on the order of one second. A group led by A. E. Baron also measured submillisecond response times using an instrument and post-processing software developed. In previous work from our group, a pressure-jump apparatus was constructed and used to measure PSP response times on the order of one millisecond.

A calibration chamber was constructed to quantify the dynamic-response characteristics of the PSPs. In this approach, CW output (450 nm) from an array of 73-blue photodiodes is used to excite a PSP-coated coupon that is fixed within a calibration cell. The resulting luminescence is detected using a photodiode. Driving a 60-Watt piezoelectric speaker driver at frequencies ranging from 100 Hz to ca. 300 kHz modulates pressure within the cell. Comparison of the intensity modulation to the drive frequency determines the temporal response of the PSP.

Figure 17 presents preliminary high-frequency-response data for a sol-gel-based PSP (- - - -) and the associated speaker-drive function (——). Currently, design-configuration changes are being implemented to allow simultaneous acquisition of transducer and PSP data. This will provide data necessary to probe PSP high-frequency response based on phase-angle delays between drive and response signals. It is clear from these data, however, that the PSP is tracking the 0.2-psi pressure modulation (about ambient) at 5.7 kHz. Current efforts focus on increasing the frequency response of the sol-gel-based PSPs, while maintaining pressure sensitivity suitable for HCF-related applications.

Future research efforts will be focused on the development of an inorganic PSP. Through the synthesis of probe molecules, mechanisms that determine the temperature and pressure capabilities of the oxygen sensing species used in PSPs can be controlled.

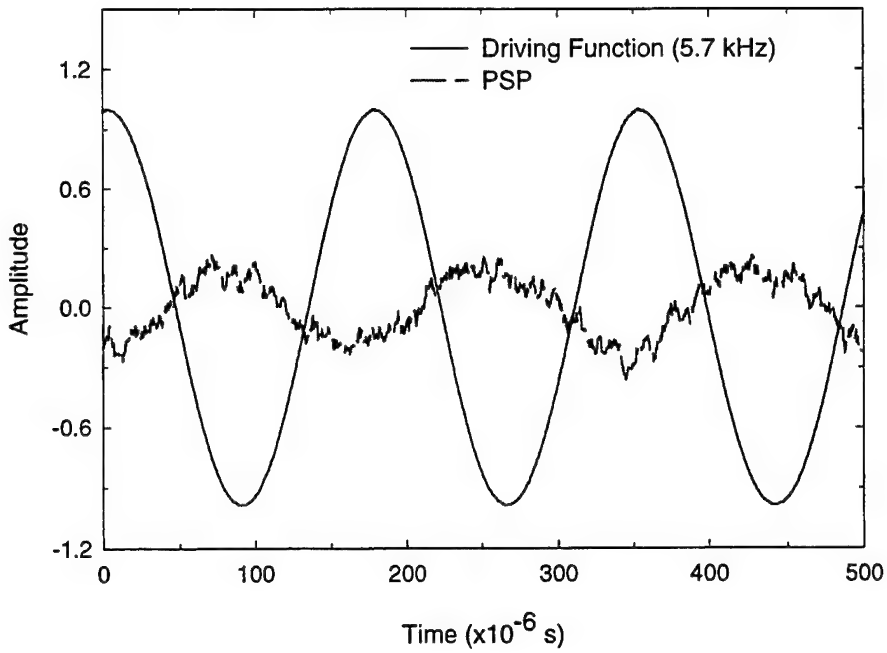

FIGURE 17. PSP Response to a 0.2-psi Pressure Modulation at 5.7 kHz

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3.2.1.2 Pressure Sensitive Paint (PSP): Light Emitting Diodes (LEDs)

FY 99-00

DESCRIPTION / PROGRESS

This is a new effort scheduled to start in November 1998. The project's objective is to address critical issues required to ensure that pressure-sensitive paints (PSPs) and thermographic phosphors (TPs) can be used in High Cycle Fatigue studies of turbomachinery. The critical issues to be addressed include probe miniaturization and paint/phosphor improvements.

Probe miniaturization requires the development of compact excitation and detection systems. Current excitation sources are heavier, bulkier, more labor-intensive, and more costly than those desired for sighted ATEGG and JTDE demonstrations. In this project, the use of high-power blue LEDs that hold promise for significant improvements in current methods of excitation for both PSPs and TPs will be investigated.

Pressure paint improvements in time response, survivability, and sensitivity at higher pressures and temperatures, and the use of thermographic phosphors as a means of temperature correction for the PSPs will also be investigated.

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3.2.2 Comparison Testing / Air Etalons

FY 96-00

DESCRIPTION / PROGRESS

The Air Etalon is a sensing concept based on Fabry-Perot interferometry. In its simplest form, a Fabry-Perot etalon consists of two mirrors separated by a certain distance, or gap. When light is incident upon an etalon, optical interference occurs; at certain optical resonance frequencies, virtually all of the incident light is transmitted through the etalon, while at other frequencies most of the light is reflected. The optical resonance frequency depends on the optical path length between the two mirrors—which of course is dependent upon the index of refraction of the material used in the gap between the two mirrors. This fact can thus be utilized to design a pressure sensor based on a Fabry-Perot etalon where the change in optical resonance is monitored as the optical path length changes as a result of changes in pressure. In this effort both solid and air-gap etalons have been investigated as pressure sensors.

A demonstration was recently conducted to show proof-of-concept of the technique. Here a macroscopic air etalon consisting of two optical glass blanks separated by a thin air gap was used. Data was acquired from the etalon as the pressure was changed from ambient to 100 psi. This experiment successfully demonstrated etalon pressure sensitivity in reflection mode, and the results agreed with the predicted pressure sensitivity for an air etalon. In Figure 18, the reflected signal data are plotted versus pressure to facilitate comparison with theory. As depicted in Figure 18, this theory fit the data quite well. Note that the reflected signal first increased then decreased with pressure. This sort of behavior is expected in an etalon when the laser is tuned to one side of the etalon peak. The maximum is where the laser wavelength matches the etalon peak wavelength. As a further test that the initial interpretation is correct, the laser frequency was scanned and the reflected signal was recorded. This data is depicted in Figure 19. Also shown in the figure is a fit to theory using the same etalon parameters used to fit the pressure data in Figure 18. The good fit demonstrates the consistency of the data interpretation and validates the air pressure etalon concept.

In the coming months, the laser instrumentation developed for this demonstration will be applied to probe thin-film air etalons etched onto silicon and ultimately metal substrates that are currently being fabricated. These etalons will be evaluated under a variety of realistic engine operating conditions and compared to the performance results of other optical pressure sensing techniques such as pressure-sensitive paints.

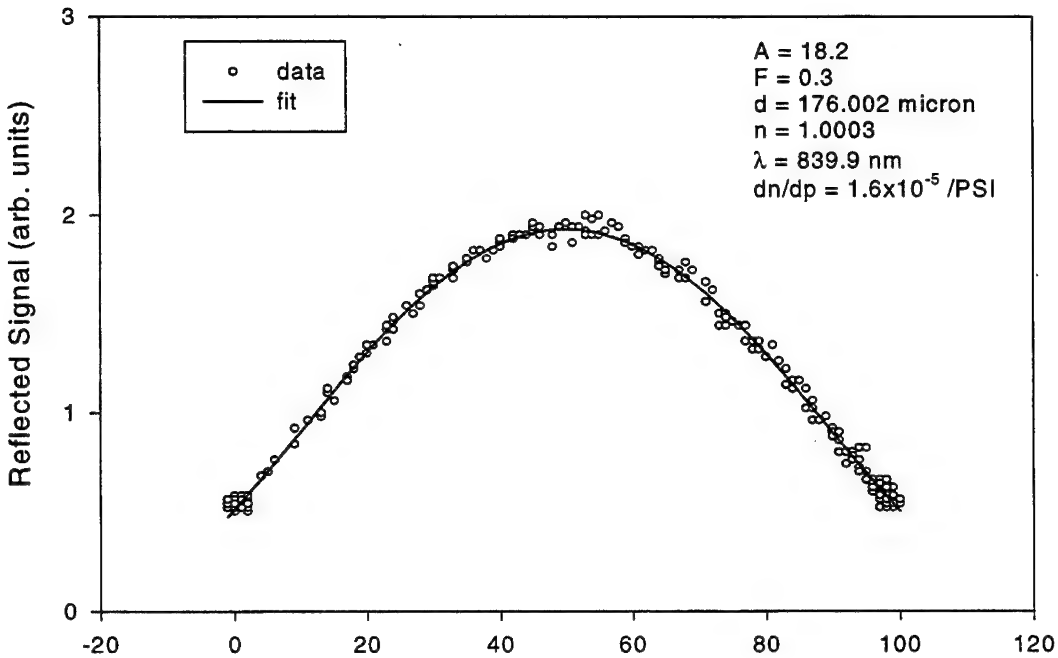

FIGURE 18. Reflected Signal vs. Pressure Change in psi for Demonstration Air Etalon

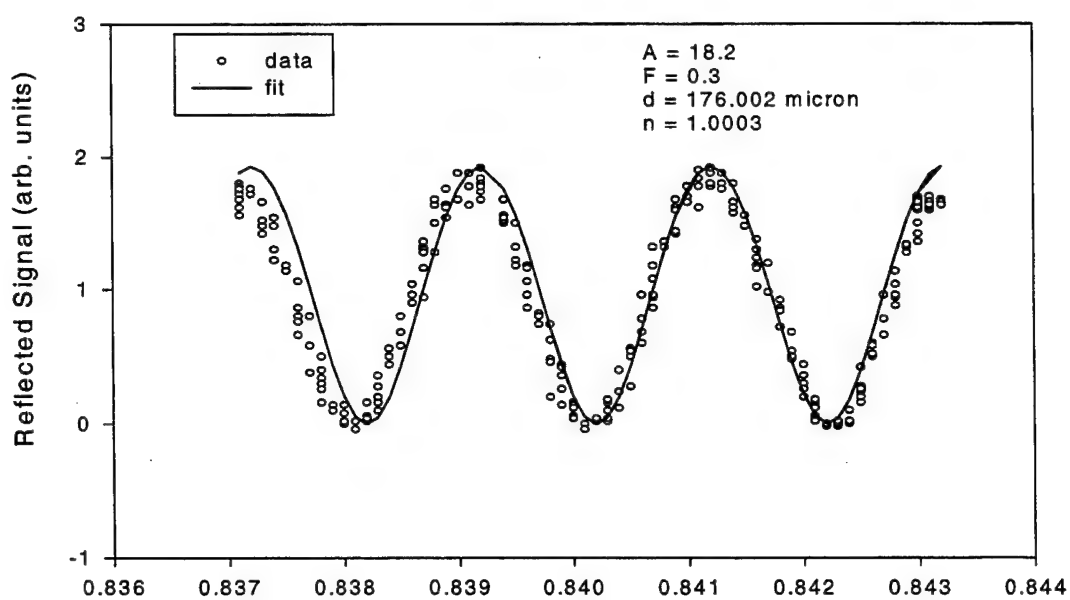

FIGURE 19. Reflected Signal vs. Wavelength in Microns for Demonstration Air Etalon

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3.2.3 Thin-film Garnet

FY 99-01

DESCRIPTION / PROGRESS

This new effort is scheduled to start November 1998. The objective of this project is twofold: (1) to investigate a new surface pressure-sensing concept, and (2) to develop a compact fluorescence detection system. The concept utilizes forester energy transfer, a process that can occur in conjunction with photoluminescence, and is very sensitive to the distance between an energy donor and an energy acceptor. Because of this spatial sensitivity, it has been exploited as a "molecular caliper." Under this effort, the use of Forester energy transfer to measure the surface pressure of thin-film garnet will be investigated. In addition, the effort will develop a compact fluorescence detection system that ideally could be used to acquire data from either the thin-film garnet, pressure paint, or thermographic phosphor.

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3.2.4 High and Low Temperature Validation of Paint/Optical Pressure Mapping

FY 99-01

DESCRIPTION / PROGRESS

A detailed comparative evaluation of the primary parameters of interest pertaining to the various dynamic pressure sensing concepts will be provided. Accuracy, dynamic response, temperature range, and sensitivity will be established. The determination of these parameters will permit the most promising sensing concept(s) to be further developed and applied the engine regions where they will provide the most useful data.

PARTICIPATING ORGANIZATIONS

Allison, GE CRD, ISSI, TACAN

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3.3 *Improved Conventional Sensors*

To date, prediction of aerodynamic forcing functions has been difficult or impossible due to lack of Computational Fluid Dynamics (CFD) fidelity, structural modeling accuracy, instrumentation effects, and insufficient characterization of instrumentation installation effects. The purpose of the projects described below is to improve the lifetime and performance of conventional sensors (eddy current/strain gages) for transition into engine health monitoring applications.

3.3.1 Non-Optical NSMS Sensor Development (Eddy Current)

FY 00-01

DESCRIPTION / PROGRESS

A successful blade tip sensor must be capable of operating in the high temperature, high pressure environment of the engine, while being sensitive to the high frequency, low amplitude vibrations which characterize the responses of modern low-aspect-ratio, unshrouded fan blades. One candidate sensor that can potentially meet these requirements is the eddy current blade tip sensor developed by Pratt & Whitney and General Dynamics Advanced Technology Systems under the joint DARPA/USAF Active Structural Control program. The sensor is mounted in the blade tip outer air seal, and employs an "m" shaped core of permeable material (powdered iron in the prototype probe) encased in an aluminum housing. Copper wire coils are wrapped around the 3 legs of the "m". When a current is passed through the two outboard coils, flux is generated which emerges from each leg and flows through the center or sensing leg in opposing directions. If these flux paths are unobstructed, the flux in the two outer legs cancels the flux in the center, and the voltage in the center sensing leg is zero. The eddy current sensor uses the principle that high frequency (1-to-5 MHz) flux is altered in the presence of conducting materials (such as titanium) to accurately indicate the position of the passing vibrating fan blade. As a blade sweeps by the face of the sensor, the flux path in the first leg is initially blocked or "excluded" and the center sensing leg will see a voltage differential due to the flux in the second outboard leg. When the blade tip is directly over the sensing leg, the flux excluded from each of the outboard legs is again equal and opposite, and a zero voltage results. As the blade sweeps across the second flux path, again a voltage differential is detected of equal magnitude but of opposite sign than the first flux path.

Although the ability to detect blade position (much like the optical noninterference stress measurement system or NSMS) was the primary goal for the eddy current sensor, it is apparent that there is another significant piece of information that can be obtained from the sensor. Whereas the zero crossing of the waveform indicates blade position, the magnitude of the waveform peaks is a direct function of blade tip operating clearance. For example, for a small operating clearance, more flux is blocked from each of the outboard legs of the sensor as the blade is centered initially over the first flux path, then the second. Therefore, the sensing leg sees the maximum amount of differential for small clearances. As the clearance is enlarged, the amount of flux blocked in each leg becomes less, and therefore the differential and magnitude of the peaks is also less.

PARTICIPATING ORGANIZATIONS

Pratt & Whitney

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3.3.2 Development of Long-Life, Less Intrusive Strain Gages

3.3.2.1 Advanced Thin-Film Dynamic Strain Gages

FY 96-01

DESCRIPTION / PROGRESS

The objective of this project is to develop and utilize static strain gages in a thin-film form for dynamic strain measurement. Thin-film sensors are fabricated directly onto the test surface using vapor deposition and lithography techniques. They do not require additional bonding agents such as adhesive or cements and are in direct contact with the test surface. Thin-film sensors in general have a thickness on the order of a few micrometers (μm) which are much thinner than the commonly used sensor wires. They have fast response times (in milliseconds), add negligible mass to the test surface, and create minimal disturbance of the gas flow over the surface. Consequently, thin-film sensors have minimal impact on the thermal, strain, and vibration patterns that exist in the operating environment and provide a minimally intrusive means of accurate measurement of surface parameters.

Under this project, the PdCr thin-film dynamic strain gages have been developed and fabricated on nickel-based superalloy and ceramic-based cantilever bars. The dynamic response of these gages are being characterized in a newly set up shaker facility under ±2,000 microstrain, 1,000 Hz to 1,800°F. The lifetime of this PdCr based thin-film gage will then be compared to the conventional foil strain gages at the room temperature.

PARTICIPATING ORGANIZATIONS

NASA Lewis Research Center, AlliedSignal Engines

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3.3.2.2 Advanced High Temperature Thin-Film Dynamic Gages

FY 96-01

DESCRIPTION / PROGRESS

The objective of this project is to develop advanced thin-film strain gages with increased temperature capability (Fig. 20). This work is based on a ceramic sensing material, Indium Tin Oxide (ITO). ITO gages have been developed under this project, and the thermal response of these ITO gages is being characterized on alumina cantilever bars to T>2,000°F. The dynamic response of the gages will also be characterized in the shaker facility under ±2,000 microstrain, 1,000 Hz, to T>2,000°F. The lifetime of this ceramic-based thin-film gage will then be compared to that of the PdCr gages and the conventional foil gages.

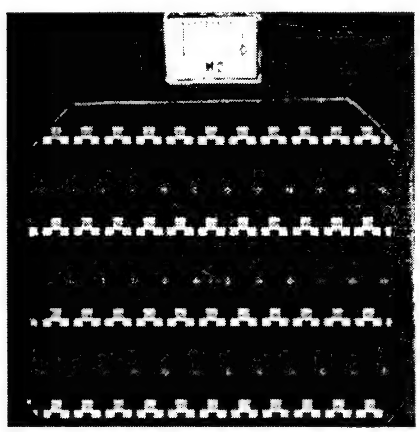

FIGURE 20. An Array of PdCr Thin-Film Strain Gage Batch Fabricated on a Ceramic Substrate

PARTICIPATING ORGANIZATIONS

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3.3.2.3 Spin Pit Validation of Strain Gages

FY 99-01

DESCRIPTION / PROGRESS

The objective of this project is to provide PdCr based thin-film dynamic strain gages for spin pit validation. NASA will supply gages installed on the structure and directions for the testing. The test organization (identify by AFRL) will supply the required signal conditional electronic controllers and devices for data collection and analysis.

PARTICIPATING ORGANIZATIONS

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3.3.2.4 Spin Pit Validation of High Temperature Strain Gages

FY 99-01

DESCRIPTION / PROGRESS

The objective of this project is to provide advanced ITO based thin-film dynamic strain gages for spin pit validation. NASA/URI will supply gages installed on the structure and directions for the testing. The test organization (identify by AFRL) will supply the required signal conditional electronic controllers and devices for data collection and analysis.

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4.0 COMPONENT ANALYSIS

BACKGROUND

The Component Analysis Action Team (Component Analysis AT) is responsible for fostering collaboration between individual HCF component analysis efforts, with the overall goal of combining with the Instrumentation and Forced Response ATs to better determine alternating stresses to within 20%. The Component Analysis AT provides technical coordination and communication between active participants involved in HCF component analysis technologies. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Component Analysis AT members meet as required (estimated quarterly) to review technical activities, develop specific goals for component analysis projects, and coordinate with the TPT and IAP. The Chairman (or Co-Chair) of the Component Analysis AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in component analysis technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

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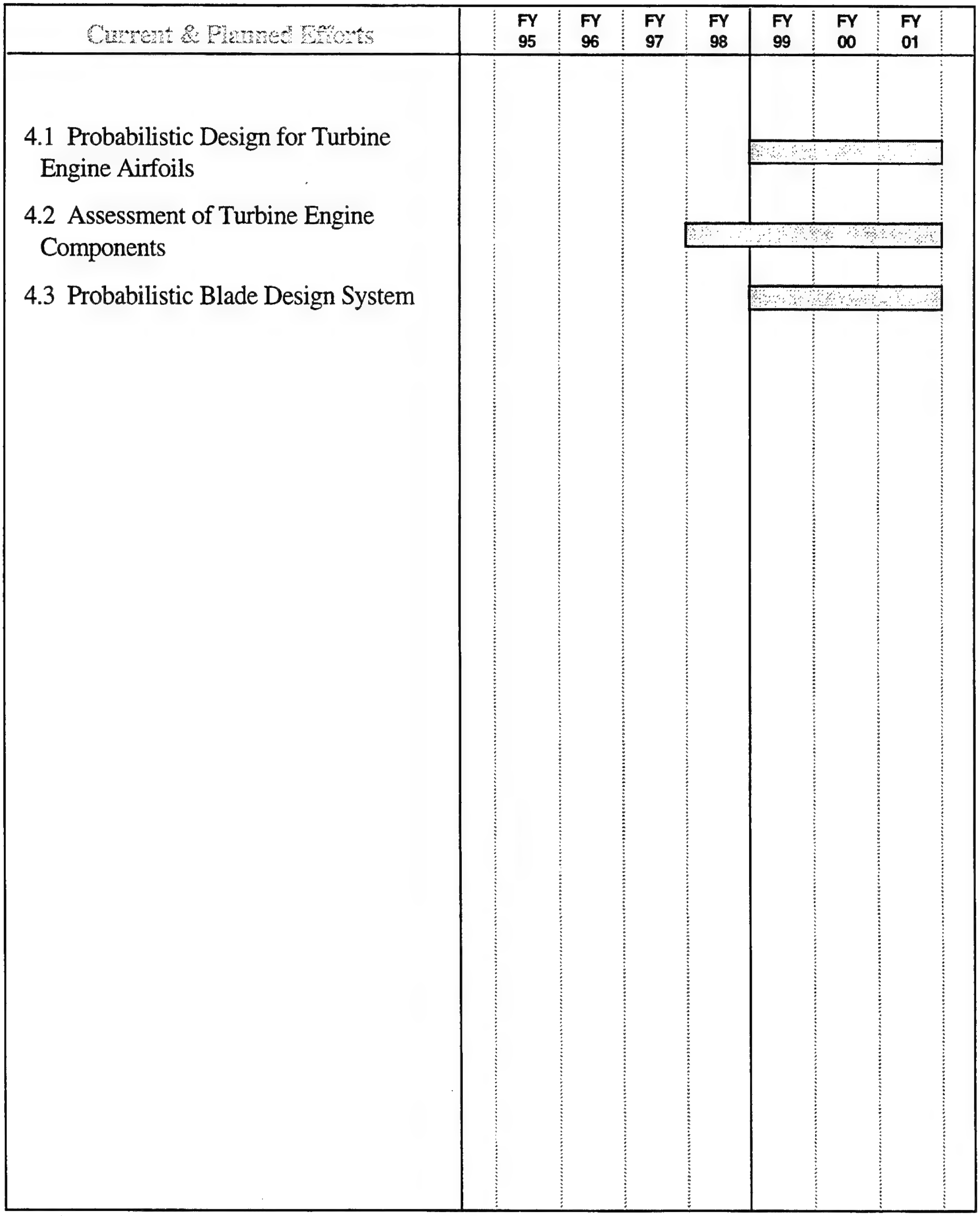
INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Component Analysis Schedule



4.1 Probabilistic Design for Turbine Engine Airfoils

FY 99-01

DESCRIPTION / PROGRESS

The objective of this project is to develop a probabilistic design system that will integrate all of the HCF technical areas and produce rigorous and efficient statistical methods for computational procedures. The consortium led by Stress Technology was selected to develop the probabilistic blade design system. Kickoff will take place in January 1999.

The task is to develop an integrated probabilistic analysis procedure for HCF prediction to be used by the US military and engine companies for improving blade life. Probabilistic models will be developed which incorporate refinements to the design process of gas turbine fan blades by the use of: (1) an efficient probabilistic framework for HCF predictions using advanced stochastic modeling concepts; (2) refined probabilistic modeling for complex space-time phenomena; (3) a probabilistic framework capable of handling highly nonlinear problems with a large number of variables and complex interactions; (4) an adaptive, multilevel, modularly structured probabilistic implementation suitable for integration into industry's proprietary systems; and (5) an integrated probabilistic framework open to future technological developments.

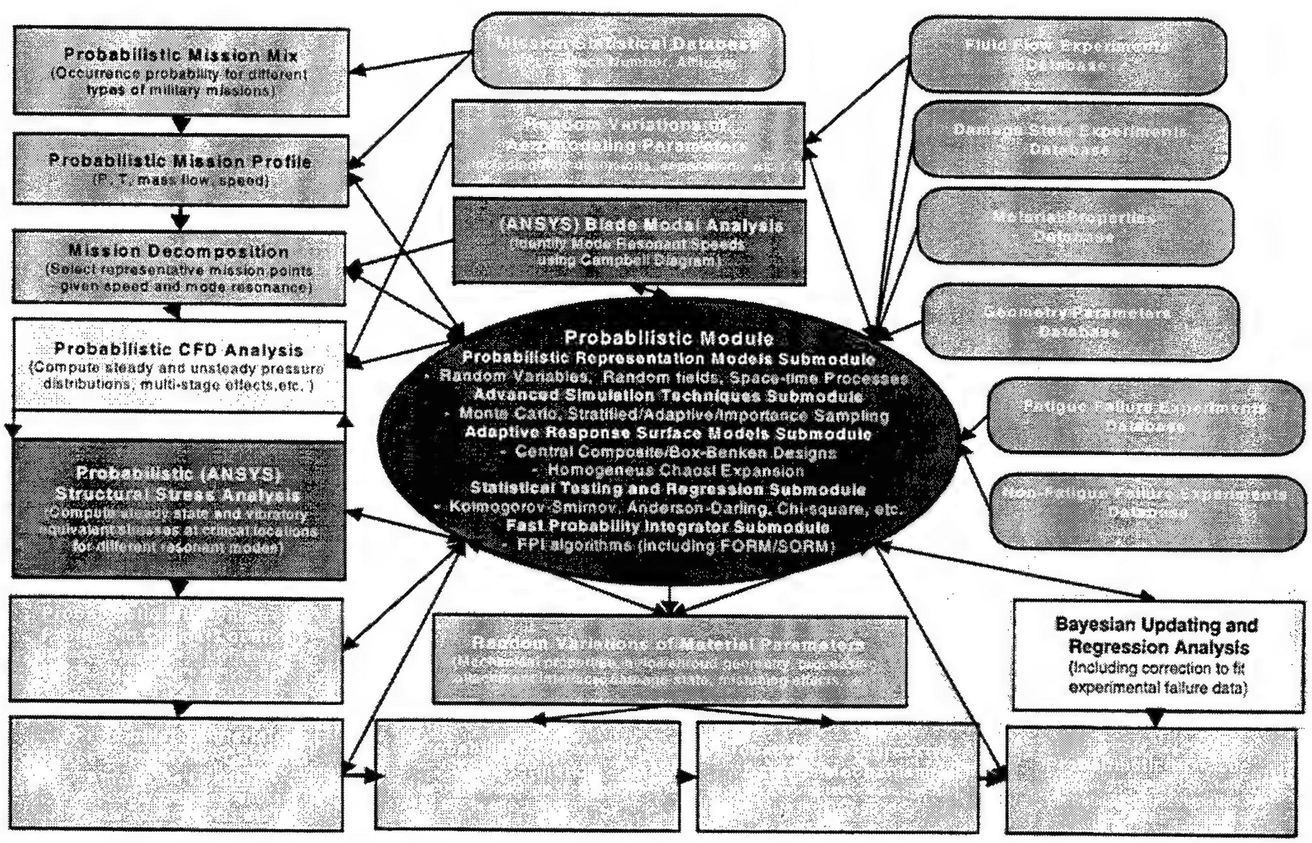


FIGURE 21. Probabilistic HCF Prediction System

PARTICIPATING ORGANIZATIONS

Stress Technology Inc., General Electric, Pratt & Whitney, Allison Engine Co., AlliedSignal Corp.

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4.2 Assessment of Turbine Engine Components

FY 98-01

DESCRIPTION / PROGRESS

This program addresses the issue of structural analysis accuracy. This is being done by developing error estimation procedures for frequency predictions, by improving the process for modeling nonlinear joints, and by several other methods.

Current design practice for turbine engine components includes methods for modeling the structural behavior of complicated interfaces, such as bolted connections and snap rings. These interfaces are both approximate and difficult to integrate into the overall structural model. The objective of this effort is to develop accurate and reliable methods and practices for modeling nonlinear interfaces. Both linear and nonlinear analysis techniques are required. In detailed stress and life prediction analysis, the analyst may need to consider the effects of pretension, contact, and friction; and a reliable nonlinear model of the connection is appropriate. For substructured analyses and prediction of natural frequencies, the joint model (Fig. 21) must be linearized to be usable. The linearized model may contain some evidence of the nonlinearity, such as properties that depend upon preload.

Initial efforts have focused on the most common nonlinear interface, a bolted joint. Detailed 3-D finite element models have been constructed of bolted connections between two and three layers of structural material. Sliding contact with friction is permitted between the structural layers and between the bolt and adjacent material surfaces. The model is subjected to bolt pretension, which establishes both contact and internal preloads. At selected preload levels, several elementary loading conditions are analyzed to obtain effective stiffness characteristics for the joint. The resulting stiffness parameters may be used to define joint properties in a larger model. Once a solution has been obtained in the system-level model, stress information can be obtained for the joint based upon the original analysis of the joint model. The results obtained from conventional methods (such as using thermal pseudo-loads to induce prestress) are being compared to more recently-developed techniques for applying prestress, such as the PRETENSION SECTION option available in ABAQUS. Current activities also include the development of consistent methods for translating the results from elementary loading of the joint model into effective stiffness properties of simple "joint elements." Analysis of a global model should

validate the effectiveness of the "element" to accurately predict resulting stress and strain for a given preset bolt load.

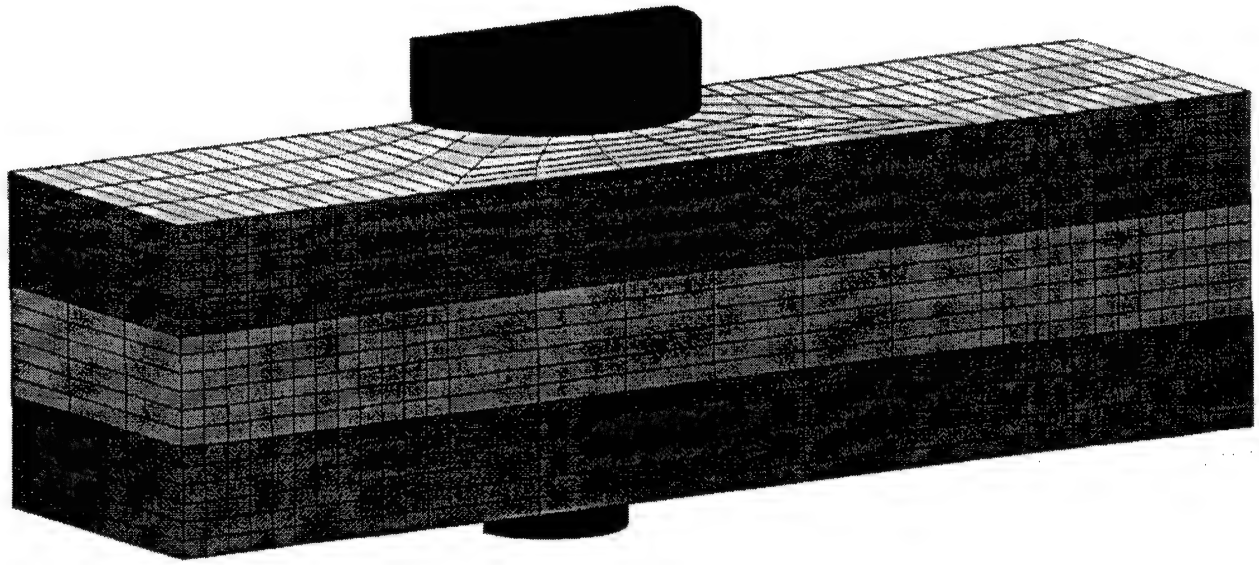

FIGURE 22. Bolted Joint for Interference Fit Modeling

PARTICIPATING ORGANIZATIONS

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4.3 Probabilistic Blade Design System

FY 99-01

DESCRIPTION / PROGRESS

The objective of this project is to develop and apply a probabilistic approach for blades in four areas of blade design: fracture screening, amplitude variability, hot spot, and mode spacing. This probabilistic design process is expected to minimize the chances for under- or over-conservative design and result in a high quality, robust product.

The classical aeromechanical design approach for blades uses deterministic design analysis to analyze the nominal blade geometry. Manufacturing variabilities are taken into account by requiring margins, or applying factors of safety, when comparing to design criteria. Distributions of design analysis parameters such as blade frequency are not estimated. The margins and factors of safety are "calibrated" by experience from previous successful and unsuccessful designs. Of course, this approach has been used in engineering design since the early days of design analysis. The downside of this approach is that it is typically overly conservative and can reject good designs. Alternatively, this approach can be nonconservative and allow bad designs to make their way to production.

In the probabilistic design process, the design analysis considers the distribution of blades that will be produced from a given design by a given manufacturing process. These input distributions, such as geometry, are used to predict the output distributions, such as frequency and stress. The design evaluation can then be based on a probability that failure criteria will be violated.

The deliverables consist of example applications showing comparisons of designs resulting from the new method with those from the traditional method. The schedule of completion dates for the four areas is: Hot Spot - May 1999, Amplitude Variability - June 1999, Fracture Screening - December 1999, and Mode Separation - June 2000.

PARTICIPATING ORGANIZATIONS

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5.0 FORCED RESPONSE PREDICTION

BACKGROUND

The Forced Response Prediction Action Team (Forced Response AT) has the responsibility of fostering collaboration between individual HCF forced response efforts with the overall goal of combining with the Instrumentation and Component Analysis ATs to better determine alternating stresses to within 20%. The Forced Response AT provides technical coordination and communication between active participants involved in HCF unsteady aerodynamics and blade response technologies. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Forced Response AT members meet as required (estimated quarterly) to review technical activities, develop specific goals for forced response programs, and coordinate with the TPT and IAP. The Chairman (or Co-Chair) of the Forced Response AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in forced response technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

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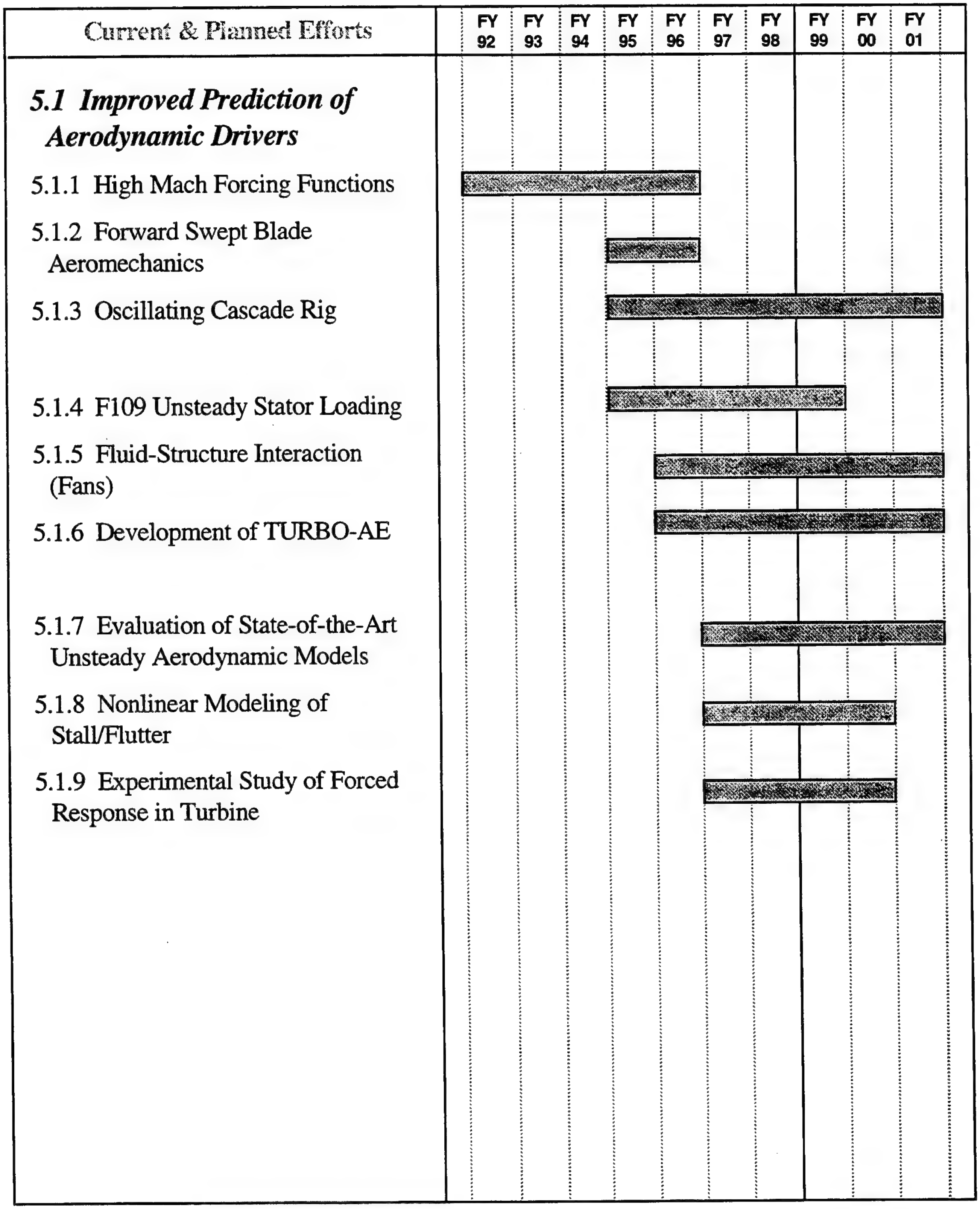
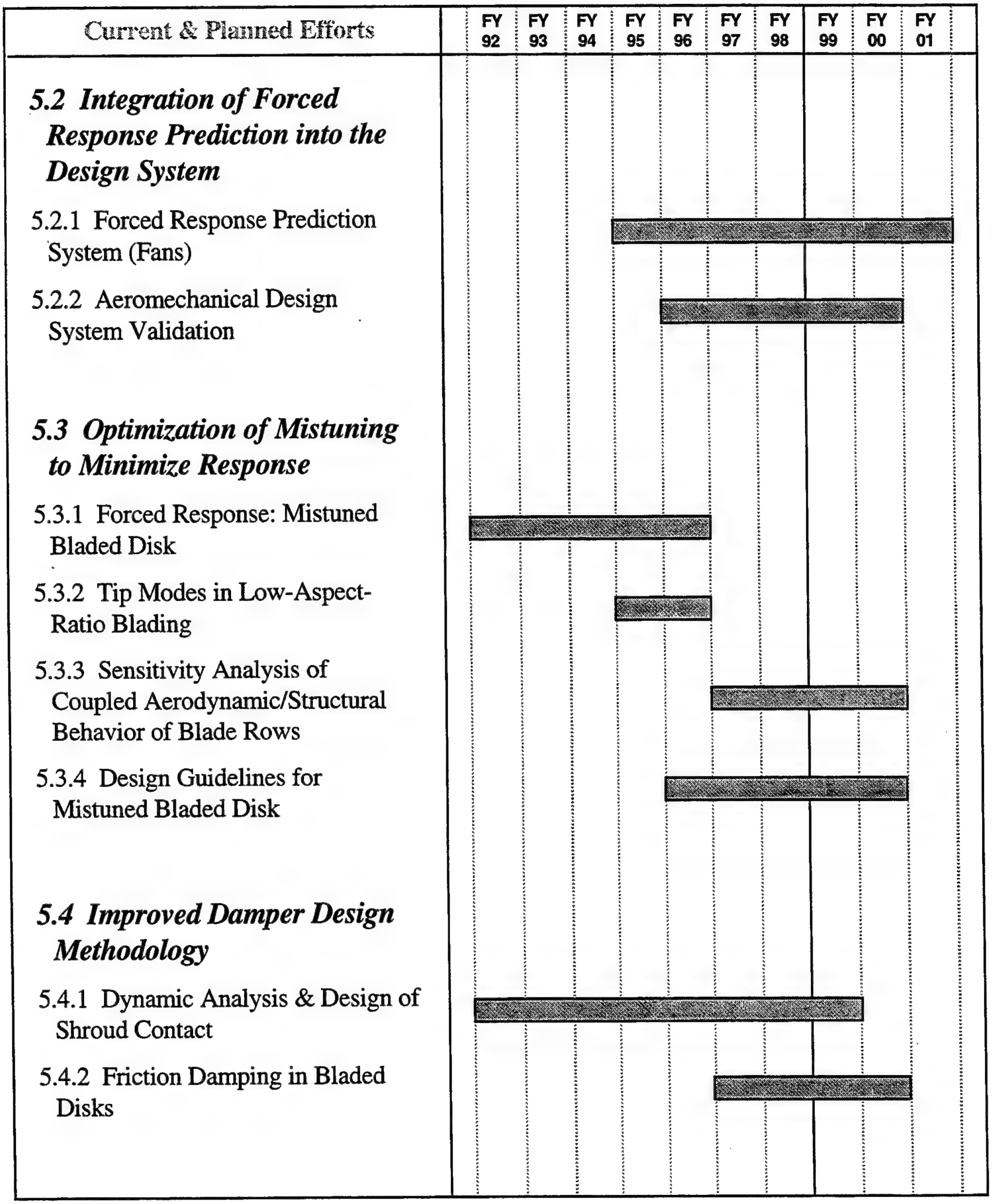
INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Forced Response Prediction Schedule



Forced Response Prediction Schedule (Cont'd)



5.1 Improved Prediction of Aerodynamic Drivers

Predicting aerodynamic forcing functions is difficult due to the lack of Computational Fluid Dynamics (CFD) fidelity and structural modeling accuracy. The purpose of the projects described below is to improve the accuracy of predictions relating to aerodynamic drivers.

5.1.1 High Mach Forcing Functions

FY 92-96

DESCRIPTION / PROGRESS

The objective of this project was to acquire and analyze data defining forcing functions generated by the wakes from rotor blades operating at high subsonic and transonic Mach numbers. Data for both the near and far wake were obtained in the Purdue High Speed Compressor Facility (Fig. 23). Concurrently, the fundamental modeling inherent in current and advanced forced response unsteady aerodynamic models was investigated. The experimental data sets were acquired to provide benchmark data for validation of advanced computational fluid dynamic analysis codes. Specific flow topics investigated included rotor wake and potential forcing function blade row interactions, inlet guide vane (IGV) wakes, high-speed rotor wake vortical and potential forcing functions, transonic flow effects on acoustic modes, airfoil row wake interactions, and separated flow effects.

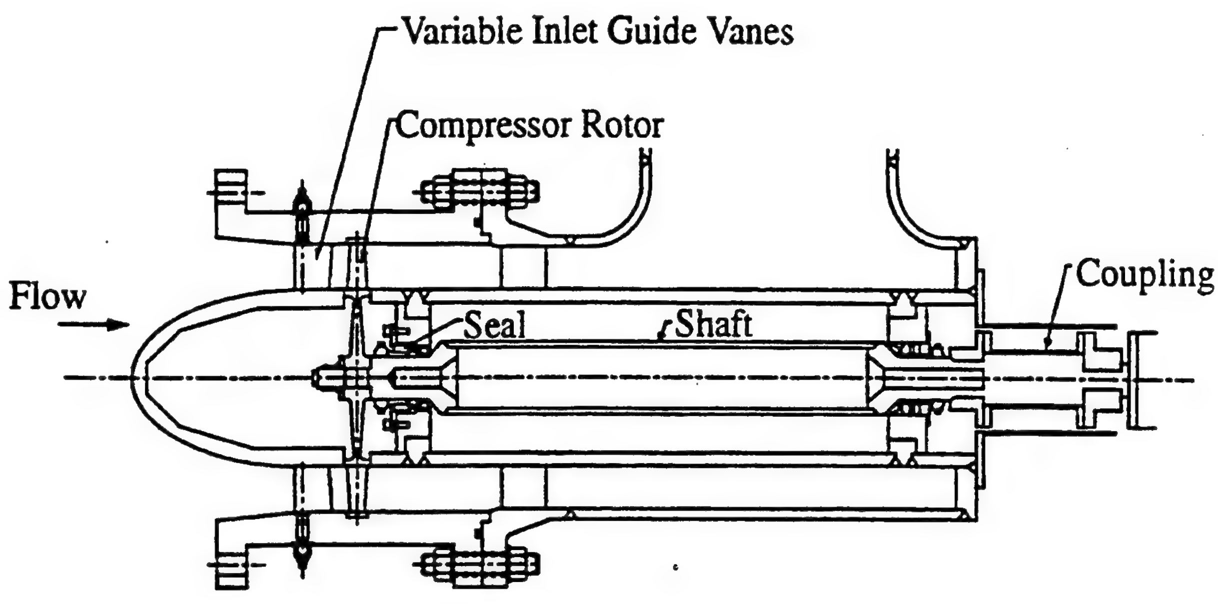


FIGURE 23. Purdue High Speed Compressor Configuration: Single Stage, 2/3 Hub-Tip Ratio Design, 18 Variable Inlet Guide Vanes, 19 Rotor Blades, Rotor Diameter 30.48 cm (12 in)

PARTICIPATING ORGANIZATIONS

GUIde (see description below), Air Force Research Laboratory (AFRL), NASA

About GUIde: The GUIde Consortium was formed in 1992 to address the problem of forced response prediction in turbine engines. It is a precursor to the current national HCF program. The consortium consists of members from USAF (Air Force Research Laboratory (AFRL) and USAFA), NASA, all four major engine manufacturers (GE, Pratt & Whitney, Allison and AlliedSignal) and academia (Ohio State, University of California at Davis, Purdue, Carnegie Mellon, University of Michigan, and Notre Dame). Together, the consortium works to address shortfalls in alternating stress prediction capability with the academic and industrial members developing or validating new codes funded by the government and industry. Some of GUIde's early codes are currently being integrated into the design systems of the engine manufacturers.

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5.1.2 Forward Swept Blade Aeromechanics

FY 95-96

DESCRIPTION / PROGRESS

The objective of this project was to acquire the data required to understand the unique aeromechanical characteristics of forward swept airfoils in order to prevent high cycle fatigue failures. To accomplish this, conventional prediction tools were used to model a rotor with forward swept airfoils. Pretest predictions were performed, and experiments were conducted to compare against the predictions, but due to funding cuts, no substantial post-test data analysis was accomplished and no final report was published. The initial comparison showed that conventional tools were as accurate for forward swept airfoils as they were for conventional airfoils. This project is complete.

PARTICIPATING ORGANIZATIONS

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5.1.3 Oscillating Cascade Rig

FY 95-01

DESCRIPTION / PROGRESS

The objective of this project is to experimentally determine airfoil surface unsteady pressure distributions at large mean incidence angles, using airfoils representative of low-aspect ratio fan blade tip sections.

The oscillating cascade rig at NASA LeRC (Fig. 24) was refurbished and modified after a shutdown period due to personnel changes. The review of previously achieved results indicated a need for careful investigation of flow quality in this rig. Measurements of flow conditions upstream of the cascade were carried out for geometrical incidence angle of 10 degrees and nominal inlet flow Mach numbers between 0.5 to 0.9. Several conclusions can be drawn from these measurements. First, the actual flow incidence angle is not equal to the geometrical one. Also, the measurements proved a decisive effect of boundary layer bleeding on the value of the incidence angle. For flows above Mach number of 0.5, the actual incidence angle is always smaller than the geometrical one. The largest difference, nearly -4 degrees, was for the Mach number of 0.9 and no bleeding. As a general rule, the angle difference increases with increasing flow Mach number and decreasing boundary layer bleeding. It seems that boundary layer bleeding also effects the periodicity of the static pressure distributions on the blades. This is a preliminary conclusion, however, because the data for flow periodicity were not fully reduced and analyzed yet. The results of this detail flow investigation will form a base for a decision about the extent of useful dynamic measurements in this cascade as required by the industry represented by the GUIde II consortium.

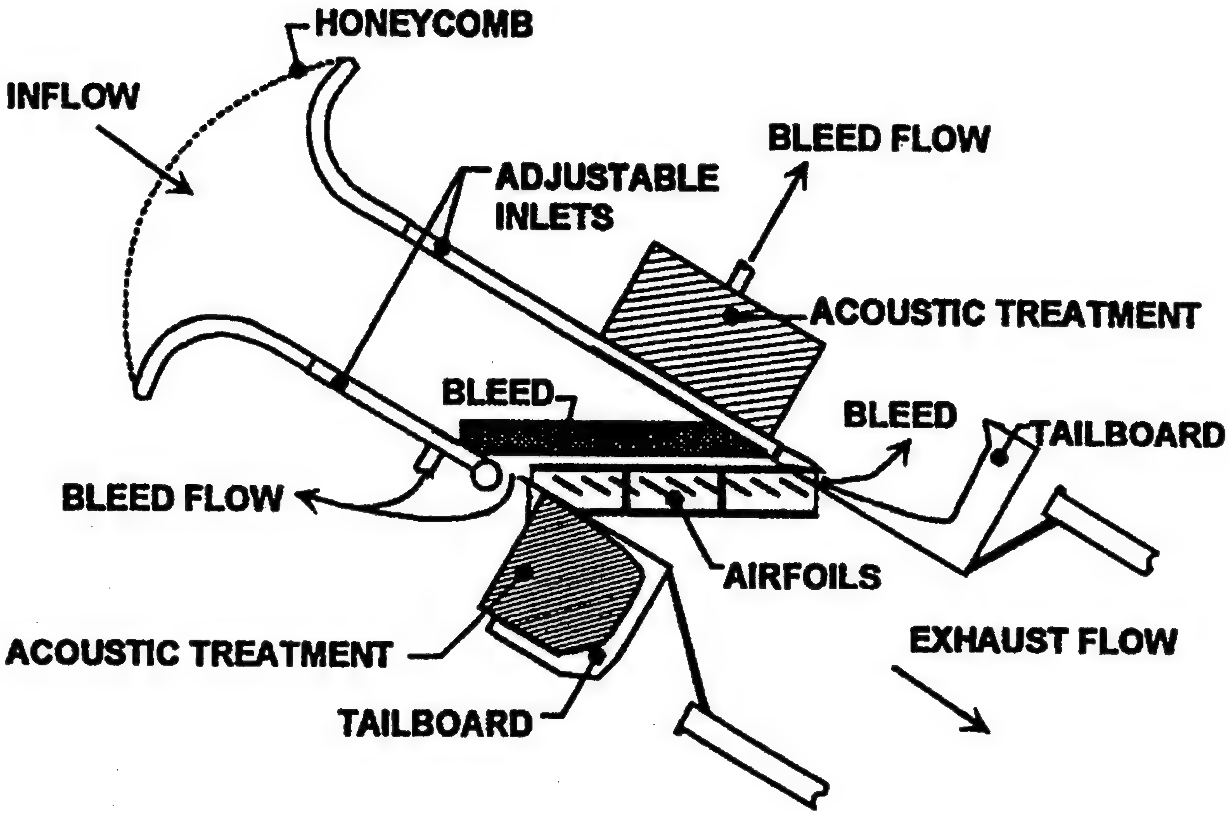

FIGURE 24. NASA Lewis Oscillating Cascade

PARTICIPATING ORGANIZATIONS

NASA-Lewis, Pratt & Whitney

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5.1.4 F109 Unsteady Stator Loading

FY 95-99

DESCRIPTION / PROGRESS

The objectives of the work are to collect, reduce, and analyze unsteady velocity data from the AlliedSignal F109 turbofan engine at the Air Force Academy in Colorado Springs, Colorado (Fig. 25). The specific areas of interest were upstream of the fan, or "fan forward" region, and upstream and downstream of the stators located behind the fan. All velocity data was taken with a two-wire hot wire, which was phase locked with the rotor.

The conclusions drawn from the analysis of the "fan forward" data are that relatively large, unsteady, velocity disturbances are present in the flow approaching the fan. The unsteady potential field generated by the individual fan blades as they rotate causes these disturbances. The disturbances radiate at acoustic speed into the oncoming flow field in a spiraling helical pattern. The amplitude of the measured unsteady velocity is as high as 50% of the mean-axial-velocity very close to the fan, and is as low as 2-5% of the mean-axial-velocity at 1.0 fan chord (2.61 in) upstream of the fan. The data collected downstream of the fan indicates the presence of a convectively-propagating wake disturbance superimposed on an acoustically-propagating potential disturbance. These results confirm that it was the combination of these two disturbances that produced the unsteady pressure response measured on the surface of the stators in a previous effort.

Current efforts are focused on the development of a small probe to measure the unsteady surface pressure distribution produced by the large-amplitude velocity fluctuations upstream of the fan. In follow-on work, this probe will be tested first in the Notre Dame cascade facility to verify its operation, then in the F-109 engine.

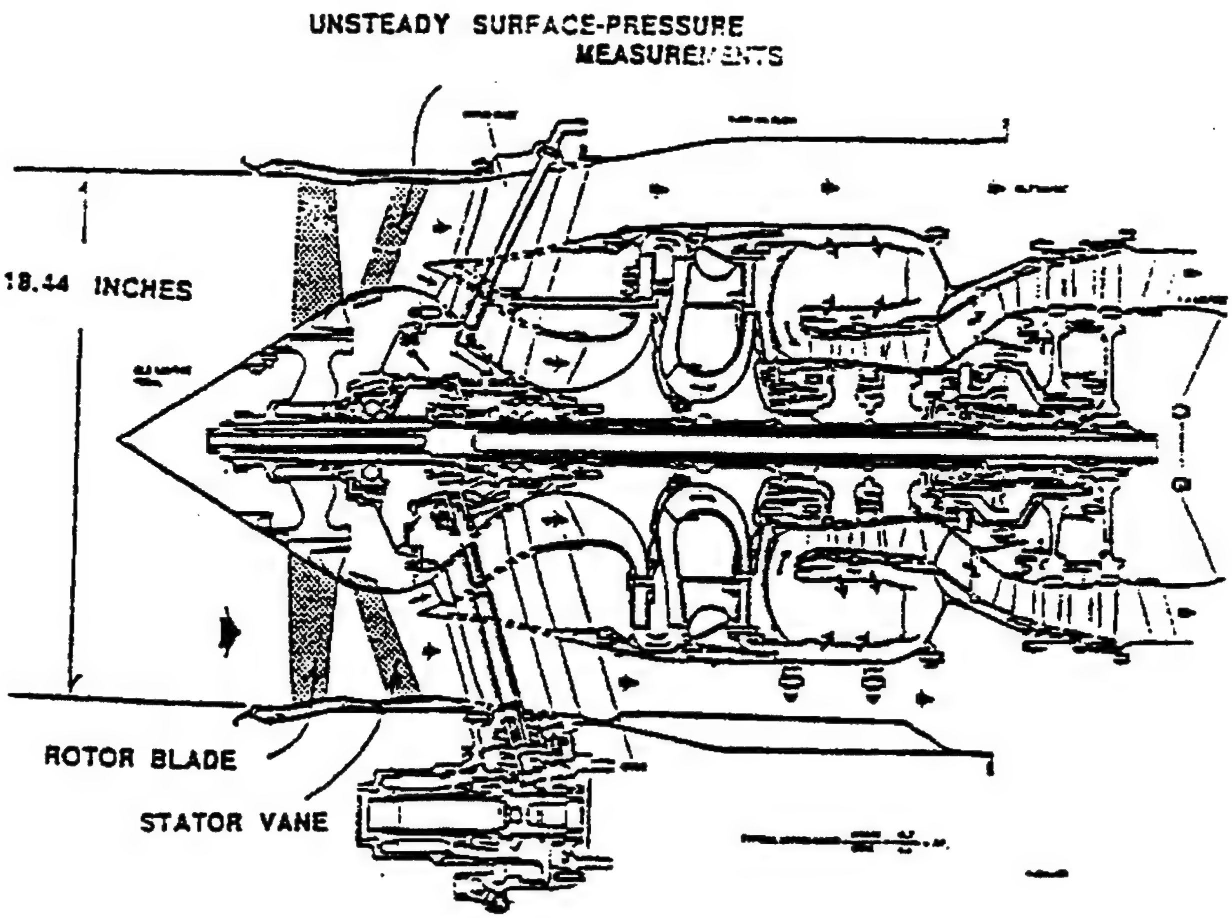

FIGURE 25. Schematic of F109 Engine Showing Location of Pressure-Instrumented Stators

PARTICIPATING ORGANIZATIONS

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5.1.5 Fluid-Structure Interaction (Fans)

FY 96-01

DESCRIPTION / PROGRESS

The objective of this project is to better understand the interaction between unsteady flows and turbomachinery structures in gas turbine engines. AFOSR did not provide a project description or progress information.

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5.1.6 Development of TURBO-AE

FY 96-01

DESCRIPTION / PROGRESS

The TURBO-AE Propulsion Aeroelasticity code is based on a three-dimensional unsteady aerodynamic Euler/Navier-Stokes turbomachinery code called TURBO. Mississippi State University developed TURBO under a grant from Lewis Research Center. The structural dynamics model of the blade in the TURBO-AE code is based on a normal mode representation. In the Flutter version of the TURBO-AE code, a work-per-cycle approach is used to determine flutter stability.

The development of the Flutter version of the TURBO-AE code has been completed, and validation by industry is ongoing. The development of the Forced Response version of the TURBO-AE code has started. Future planned activities that have not yet been funded include multistage analyses and new turbulence models.

PARTICIPATING ORGANIZATIONS

NASA Lewis

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5.1.7 Evaluation of State-of-the-Art Unsteady Aerodynamic Models
FY 97-01

DESCRIPTION / PROGRESS

The objective of this project is to evaluate the capabilities of current state-of-the-art unsteady aerodynamic models that attempt to predict the gust and oscillating airfoil response of compressor and turbine airfoils over a range of realistic frequencies and loading levels. Additionally, the effect of the aerodynamic forcing function on gust response, and the effects of three-dimensional flow on airfoil oscillation will be investigated. Codes to be analyzed are primarily NASA Lewis codes, such as Nphase, Sflow, Linflow, and Linflux.

This was originally a GUIde Consortium effort, but GUIde's participation ended when principle investigator left academia. Wright State University will continue this research in the near future.

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Air Force Research Laboratory (AFRL), Wright State University

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5.1.8 Nonlinear Modeling of Stall/Flutter

FY 97-00

DESCRIPTION / PROGRESS

The objective of this project is to investigate the use of reduced-order modeling (ROM) techniques to simulate linear and nonlinear stall flutter in cascades. Research will be conducted in three main areas: (1) the development of a time-domain, linearized Navier-Stokes analysis; (2) the development of an efficient eigenmode extraction code for large systems of equations; and (3) the development of reduced-order modeling techniques to model nonlinear unsteady flows, especially phenomena such as hard flutter boundaries and limit cycle behavior.

Use of the Harmonic Balance technique for the nonlinear flow solver has been investigated. A frequency domain Proper Orthogonal Decomposition (POD) technique has been developed to compute basis vectors and linear ROMs of unsteady channel flow. These efforts are potentially much faster than conventional time-marching solutions and are computationally efficient. Using the POD technique, a nonlinear ROM will be developed for unsteady viscous flow in cascades. Analysis codes will be transitioned to industry through GUIde Consortium.

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5.1.9 Experimental Study of Forced Response in Turbine

FY 97-00

DESCRIPTION / PROGRESS

The purpose of this project is to develop an understanding of the forcing function, aerodynamic damping, and structural damping at actual engine conditions for high-frequency vibration of turbine blades. An actual AlliedSignal TFE731-2 High Pressure Turbine will be studied in the Gas Turbine Laboratory at Ohio State University. The original blades, which had a severe high-frequency vibration problem, will be evaluated in conjunction with two other turbine designs. For each configuration, unsteady surface pressures and blade response will be measured at actual operating conditions. The result of this research will be a database that can be used to validate future prediction codes.

The UNSFLO Computational Fluid Dynamics (CFD) simulation of turbine stage and the ANSYS finite element method (FEM) analysis of blade natural frequency have been completed. The test hardware (Fig. 26) is on site and instrumented, and data acquisition is currently in progress. Measurement of unsteady surface pressure and blade response at actual engine conditions will occur in the near future.

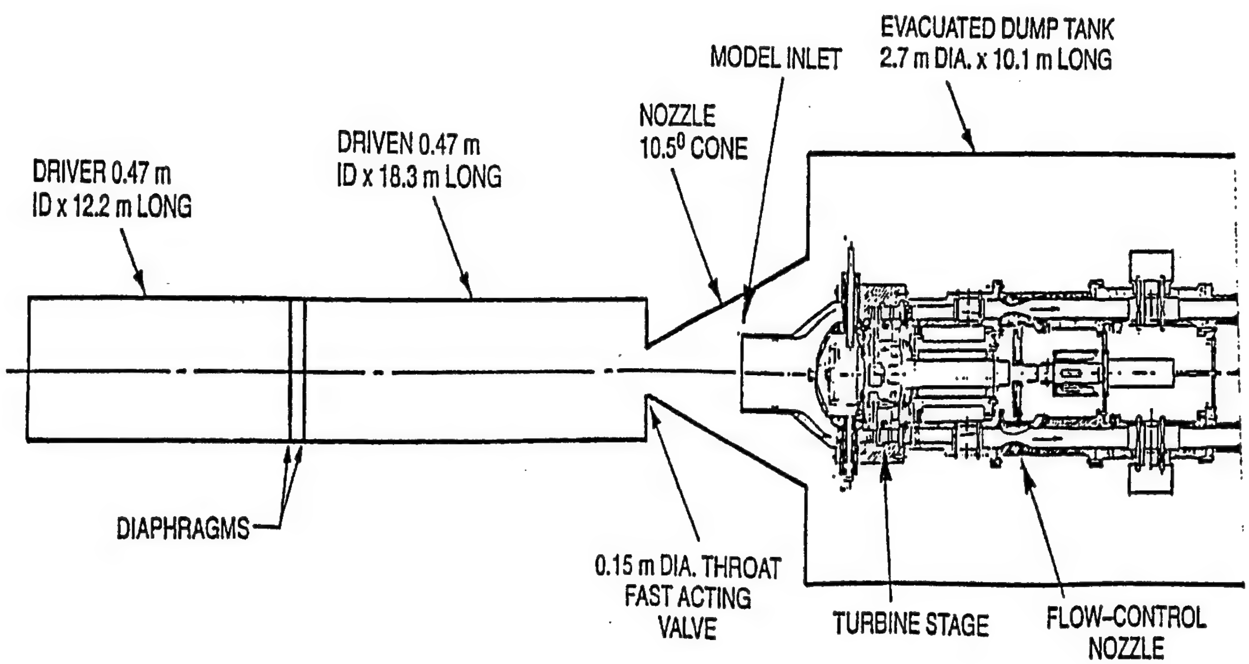

FIGURE 26. Schematic of Experimental Apparatus

PARTICIPATING ORGANIZATIONS

GUIde, NASA

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5.2 *Integration of Forced Response Prediction into the Design System*

The following projects are in place to integrate forced response prediction into the design system.

5.2.1 Forced Response Prediction System (Fans)

FY 95-01

DESCRIPTION / PROGRESS

The objective of this project is to develop and validate NASA's new Forced Response Prediction System design tools. Three codes are being developed for forced response predictions: FREPS, FREED and TURBO-AE. FREPS uses two-dimensional linearized potential unsteady aerodynamics and is the fastest running of the codes. The development and validation of FREPS is complete and is being followed by the development of FREED. FREED uses steady Euler aerodynamics from the TURBO code, and linearized three-dimensional unsteady Euler aerodynamics from LINFLUX. LINFLUX is a turbomachinery code developed under a contract from NASA Lewis Research Center. FREED being a linearized code and TURBO-AE being a fully non-linear code are complimentary. Both codes are based on the same algorithm, but each provides a different level of physics modeling and has different computational requirements. The TURBO-AE code, described elsewhere in this report, is the longest running of the three codes. The structural dynamic model of the blade for the three codes is based on a normal mode representation.

Initial work has been focused on installing the LINFLUX code on different computer workstations, and exercising the code to gain familiarity with its operation. An interface code is required to convert the steady TURBO solutions for use with LINFLUX. The interface code is being updated to work with the latest version of TURBO. In addition, the interface code is being modified to work on the Cray C-90, where the steady TURBO solutions are currently being run. Plans include improvement of the steady solver to obtain faster convergence and to obtain solutions with reduced numerical losses. In addition, the FREED code will be validated using configurations that are of current interest to industry.

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5.2.2 Aeromechanical Design System Validation

FY 96-00

DESCRIPTION / PROGRESS

The response of an existing rotor has been measured and a full rotor finite element method (FEM) analysis has been performed. Next, the FEM code will be coupled with a model of the inlet flow field and the resulting vibratory stresses will be predicted. The predictions will be compared with bench data and recommendations for additional code development will be made.

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5.3 *Optimization of Mistuning to Minimize Response*

Mistuning is a mode localization process in which certain blades vibrate with higher amplitudes than other blades as a result of slight blade-to-blade variations in geometric and material properties. The projects described below are aimed at optimizing mistuning to minimize forced response.

5.3.1 Forced Response: Mistuned Bladed Disk

FY 92-96

DESCRIPTION / PROGRESS

Mistuning is a mode localization process in which certain blades vibrate with higher amplitudes than other blades as a result of slight blade-to-blade variations in geometric and material properties. Under this effort, a reduced-order modeling technique for mistuned bladed disks was developed. The resulting code, REDUCE, can calculate natural frequencies and mode shapes for a tuned case and for a prescribed mistuning pattern. REDUCE allows the user to obtain a frequency sweep output for the maximum blade response amplitude or for all blades. A Monte Carlo analysis is performed to determine the blade response amplitude and deviations. Pre- and post-processing capabilities allow for use of NASTRAN and ANSYS files. The REDUCE code has been transitioned to the industrial GUIde members.

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5.3.2 Tip Modes in Low-Aspect-Ratio Blading

FY 95-96

DESCRIPTION / PROGRESS

The objective of this project was to develop a basic understanding of sources of variability in high-frequency motion in low-aspect ratio blades, and to develop codes based on this research. The two thrusts of the research were (1) to understand the effect of taper angle and bluntness of the leading edge of the airfoil on the vibratory response of high-frequency tip modes, and (2) to develop an understanding of the manner in which closely spaced modes interact to produce highly variable response. For the first thrust, using a tapered beam as a first-ordered approximation for a low-aspect ratio blade, it was determined that the magnitude and location of maximum stress were functions of the truncation factor. For small truncation factors, the response of a high-frequency mode was extremely sensitive to variations in the tip thickness. For the second thrust, for an airfoil with two modes of nearly equal frequency, the modes are highly sensitive to minor variations in blade geometry. Codes developed under this effort have been transitioned to GUIde members.

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5.3.3 Sensitivity Analysis of Coupled Aerodynamic/Structural Dynamic Behavior of Blade Rows

FY 97-00

DESCRIPTION / PROGRESS

The objectives of this project are (1) to develop realistic computational models, (2) to predict the aerodynamic forcing and damping in turbomachine cascades, (3) to develop analyses for computing the sensitivity of aerodynamic performance and the unsteady aerodynamic and structural dynamic behavior of the cascade due to changes in blade geometry, and (4) to develop optimization routines for computing blade geometries which minimize the aerodynamic response while maintaining high efficiency.

Sensitivity analysis for 2D steady and linearized unsteady Euler flow using multiple techniques has been completed. Viscous terms have been added to extend this capability to steady and unsteady Navier-Stokes equations. 2D aerodynamic sensitivity analysis for "typical" airfoil section is currently being developed. Future work includes application of optimization algorithms to coupled aeroelastic models to minimize aeroelastic response, adaptation of a 3D Euler sensitivity analysis, coupling of algorithms to finite element analysis for sensitivity analysis of blade structure, and application of a complete methodology to representative geometries.

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5.3.4 Design Guidelines for Mistuned Bladed Disks

FY 96-00

DESCRIPTION / PROGRESS

The objective of this project is to develop a program for analysis and design of mistuned bladed disks based on REDUCE (developed under GUIde I). Update 2.1 of REDUCE has been released to GUIde members. This new version allows for shroud modeling, individual mode mistuning, and a menu-driven translator for generation of input files from various analysis codes. An experimental investigation has been initiated to generate validation data for intentionally mistuned systems. Modifications will then made to the original REDUCE code based on these findings.

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5.4 *Improved Damper Design Methodology*

Projects to improve damper design methodology are described below.

5.4.1 Dynamic Analysis & Design of Shroud Contact

FY 92-99

DESCRIPTION / PROGRESS

The objective of this project is to develop a program to predict blade vibration for rotors having shrouds and/or platform dampers (friction dampers). The completed GUIde I effort was instrumental in the development of BDAMPER, which facilitates analysis of blade-to-ground dampers, blade-to-blade dampers, shroud contact interfaces, and wedge dampers. The GUIde II effort focuses on the stick-slip transition for elliptical motion in the shroud contact plane.

Under the GUIde II effort, development of specific BDAMPER modules is continuing. BDAMPER 6.0 has been delivered, transitioned to GUIde industrial members, and successfully utilized in damper redesign. Analysis of constrained and complex mode shapes and initial 3D kinematics was completed earlier this year. Work in 3D contact kinematics continues, and advanced subroutines for BDAMPER will be transitioned to industry.

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5.4.2 Friction Damping in Bladed Disks

FY 97-00

DESCRIPTION / PROGRESS

The objective of this project is to investigate the extreme sensitivity of shrouded bladed dynamics to small changes in design in order to develop an improved understanding of the dynamic response of shrouded disk systems. The final result will be a set of design tools and guidelines to develop robust shrouded bladed disk systems.

Nonlinear Reduced-order Model (NMCC), which models the full system, has been developed. A friction model has been added to the blade vibration analysis code BLDVIB. 3D contact model for the prediction of resonant response of shrouded blade systems has been developed and is currently undergoing validation evaluation. Upon validation, the 3D model will be incorporated into BLDVIB.

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6.0 PASSIVE DAMPING TECHNOLOGY

BACKGROUND

The Passive Damping Technology Action Team (Damping AT) has the responsibility of fostering collaboration between individual HCF passive damping efforts with the overall goal of damping component resonant stress by 60% for fans and turbines. The Damping AT provides technical coordination and communication between active participants involved in HCF passive damping technology. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair and selected Damping AT members meet as required (estimated quarterly) to review damping activities, develop specific goals for passive damping programs, and coordinate with the TPT and IAP. The Chair (or Co-Chair) of the Damping AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in damping technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

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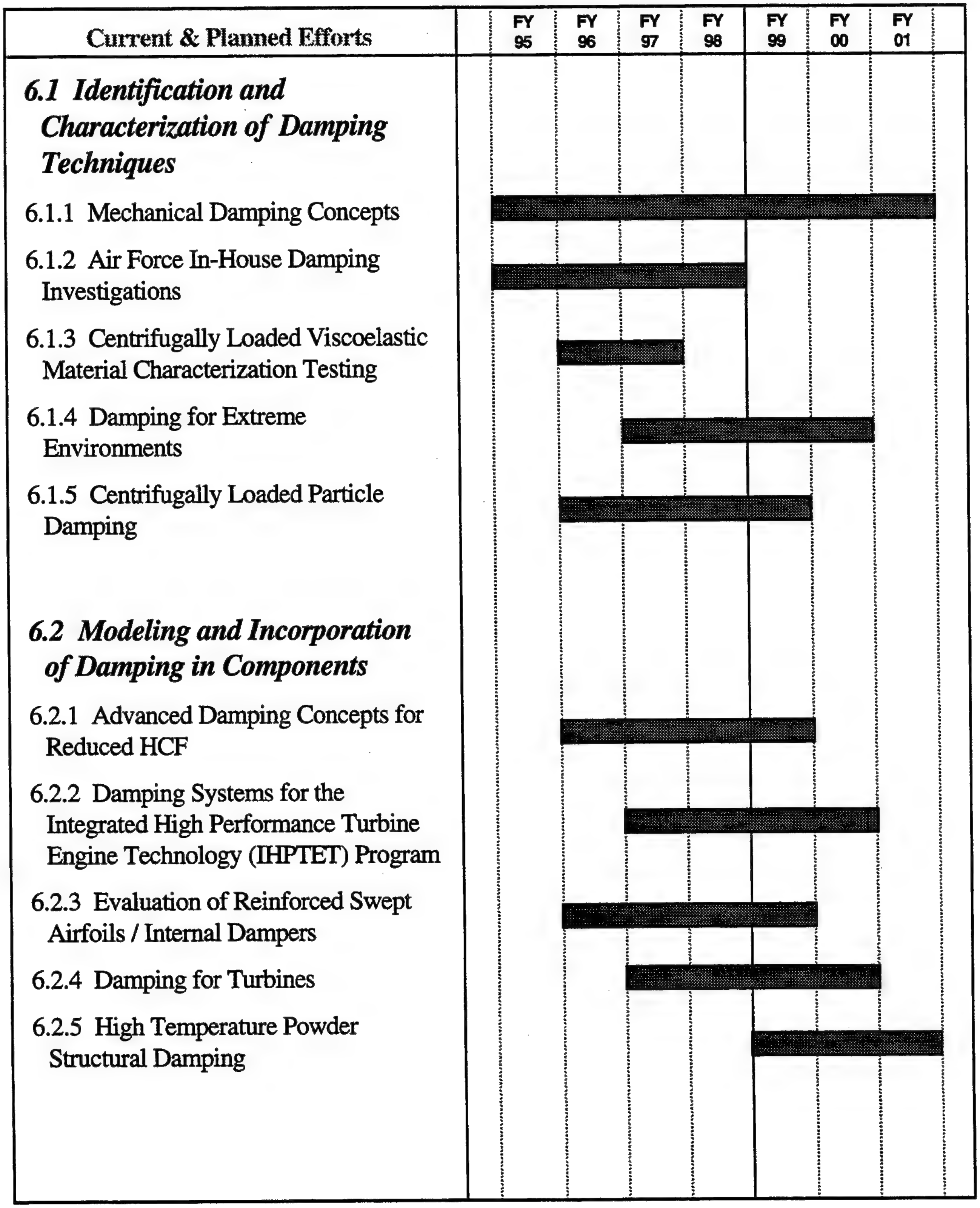
INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Passive Damping Schedule



6.1 *Identification and Characterization of Damping Techniques*

Four types of passive damping systems, judged to have a reasonable chance of effectively damping rotating engine components, are being investigated: (1) friction damping systems, which have been used in platform and shroud applications and now show promise as devices internal to blades (2) viscoelastic material systems, which have mature design optimization procedures and are now being designed to function under high centrifugal loads (3) particle damping systems, which have the potential of providing damping independent of temperature, but require a lot of effort in characterization and design optimization, and (4) powder damping systems, which are an extenuation of the tribology of dry film lubricants, have temperature independent damping, and require the most work in the development of acceptable systems.

6.1.1 Mechanical Damping Concepts

FY 95-01

For the past year, researchers at NASA Lewis Research Center (LeRC) have been investigating several damping methods for rotating blades. Dr. Gerald Brown, Senior Research Engineer, and Dr. Kirsten Duffy, National Research Council Research Associate, have been studying impact damping both theoretically and experimentally. Oral Mehmed, Senior Research Engineer, has been working with Dr. John Kosmatka at the University of California, San Diego to study viscoelastic damping in composite blades. Mehmed has also designed a new hub for spin testing the damped blades in the NASA Dynamic Spin Facility.

Initial testing of impact dampers in flat aluminum plates was completed in 1997, with one configuration successfully damping vibrations at nearly 1,700 G's. In 1998, the damper designs were improved and made smaller to insure better operation at higher G's. These enhanced designs were fabricated and will be tested in the Dynamic Spin Facility in November-December 1998. In order to show the feasibility of impact damping for very thin blades, impactors as small as 0.031" in diameter have been obtained and will be tested in 1999.

Also in the 1998 test, several tuned-mass/impact dampers will be studied. Dr. Ronald Bagley, a visiting professor from the University of Texas at San Antonio, generated this idea in the summer of 1998. The frequency of motion of the damper depends on the rotor spin rate, causing it to function along an engine order line. At higher amplitudes, the damper will work as an impact damper, and at lower amplitudes as a tuned-mass damper.

Finally, a new damper type called the fluid-baffle damper will be spin tested for the first time. This damper should be effective only in a high acceleration field, such as exists in rotating blades.

Research is also being conducted in the area of integrally damped composite blades. The objective of this research is to develop technology to passively damp blades made of composite material by designing and fabricating the blades with viscoelastic material built-in. Earlier analytical and experimental research with spinning composite plates showed that the concept works and the damping benefits are significant. New research in 1998 is aimed at developing and demonstrating an integral damping design for a scale model of a modern composite fan blade. The damping design is focused on maximizing the blade damping for a specific rotating speed range and mode, while maintaining the initial structural static and dynamic properties. At this time, a blade design is complete and fabrication

has started. Non-spinning structural characterization is planned at the University of California, and spinning structural characterization is planned at the NASA Dynamic Spin Facility (Fig. 27).

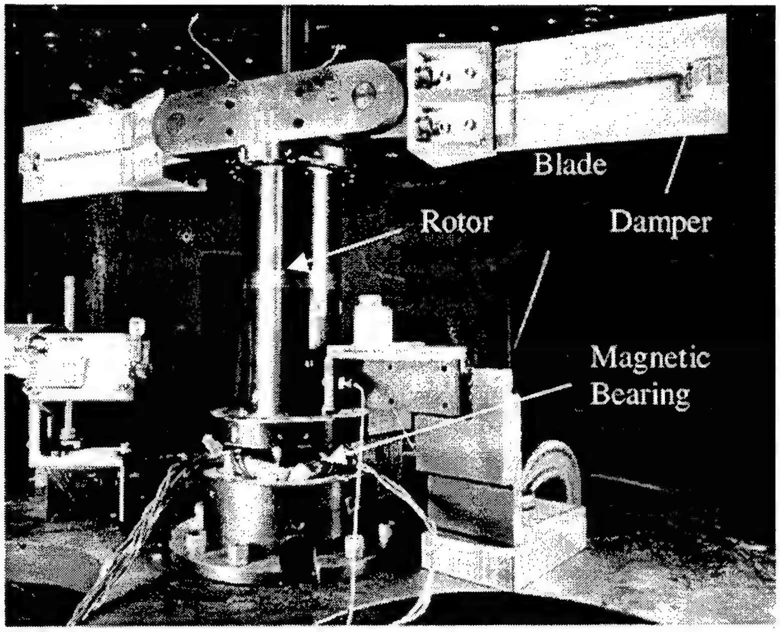


FIGURE 27. Dynamic Spin Facility, NASA Lewis Research Center

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NASA, University of California

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6.1.2 Air Force In-House Damping Investigations

FY 95-98

DESCRIPTION / PROGRESS

The objective of the project was to provide insight into the problem of determining modal damping in a bladed rotor with mistuning. Damping measurements are usually made assuming a single degree of freedom model for the system. In a bladed rotor with slight mistuning of the resonant frequencies of individual blades, a frequency response peak can be the superposition of several closely coupled resonant system modes. Errors in measured values of modal damping caused by these closely coupled system modes are referred to as damping smearing.

A generic model of a first stage jet engine fan was designed and fabricated for experimental investigations. The model was designed to capture the dynamic characteristics of a real fan and yet be relatively simple and inexpensive to analyze, fabricate and test. The design requirements established for the model fan were as follows:

- The fan must have at least eight blades.
- The disc (hub) geometry must be similar to that of a real fan.
- The blade aspect ratio, frequencies, and mode shapes similar to those of real fan blades.
- Nominal blade modal damping ratios ($\zeta \leq 0.1\%$) must be very low.
- The standard deviation of blade frequency distribution (mistuning), $\sigma \cong 1.0\%$.

The model fan design was finalized using the requirements described above. An eight-bladed design was selected. The fan diameter was chosen to be 36 inches. The hub was cylindrical, with a diameter of 12 inches and a length of 6.4 inches. The model is shown in Figure 28.

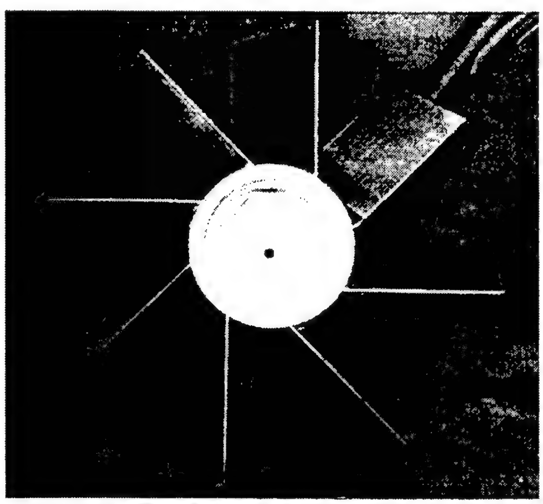

FIGURE 28. Bladed Disk Experimental Model

The effect of hub stiffness (wall thickness) on blade-to-blade coupling was considered. Initial testing of the solid hub model revealed that significant blade-to-blade coupling existed with a half-inch wall thickness. As a result, modal tests were performed only on the half-inch-wall hub. The coupling exhibited in this case was sufficient to warrant an investigation of damping smearing. It was decided to concentrate on the second bending and the two-stripe modal families. Two damped configurations were tested. In each configuration, damping was added to a single blade. The first configuration was

designed to localize the damped blade thereby eliminating damping smearing. The second configuration was designed to cause the damped blade to couple with undamped blades and result in damping smearing.

The damping treatment selected for the model fan is shown schematically in Figure 29. The design consisted of a 0.005-inch-thick layer of 3M ISD113 viscoelastic material (VEM) and a 0.005-inch-thick aluminum constraining layer.

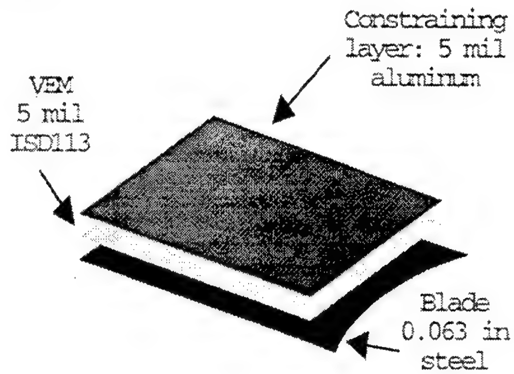

FIGURE 29. Schematic of the Damping Treatment for a Single Blade

The predicted frequencies and modal damping ratios for the target modes are listed in Figure 30.

Undamped		Damped	
f_d(Hz)	ζ (%)	f_d(Hz)	ζ (%)
412.1	0.05*	413.7	0.75
767.8	0.05*	774.6	1.05

* estimates based on experience

FIGURE 30. Finite Element Method (FEM) Damping Predictions

A modal test was performed to identify the 2nd bending mode family. The test was conducted using the same procedure described for the undamped test article. The resulting natural frequencies, mode shapes and modal damping ratios are shown in Figure 31. In this modal family, we hoped to see the highest frequency mode localized to blade 5 with 0.8% modal damping. All other modes should be lightly damped ($\zeta \cong 0.05\%$) with no contribution of blade 5 in the mode shape.

The results shown in Figure 31 fail to confirm the expectations. First, the highest frequency mode is not localized to blade 5. In fact, there are two modes with virtually equal frequencies at 412.0 Hz. One of these modes has maximum amplitude in blade 5, but there is also participation in blade 6. Although this mode is considerably lower in frequency than the eighth mode, it has some participation from blade 5. When the test results in Figure 31 are compared with the undamped model test results in Figure 32, the first six frequencies and mode shapes are seen to be nearly identical. The only significant difference between the two cases is the increased damping in the third mode. The highest two modes in the undamped test show some similarity in shapes with the damped case, but their frequencies have coalesced. In summary, adding damping to blade 5 caused some smearing to other

blades/modes even though this case was designed to avoid smearing. If this model had been subjected to a spin test, the results would have shown blade 5 had 0.5% added damping instead of the correct value of 0.75%.

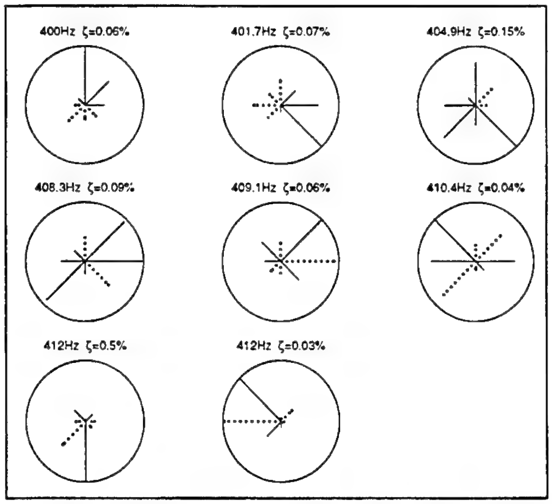

FIGURE 31. The Second Bending Family of Modes When Blade 5 Is Damped (Experiment)

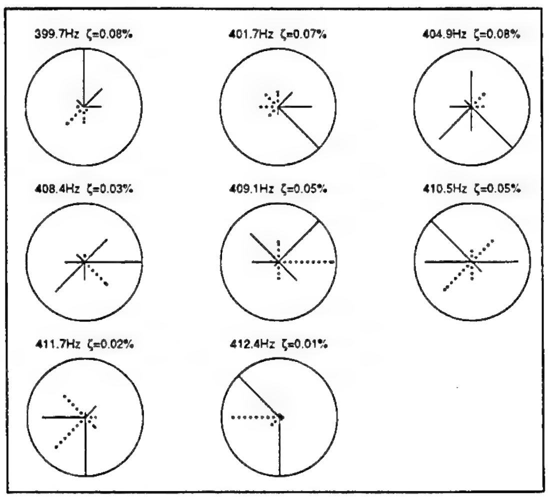

FIGURE 32. The Second Bending Family of Modes for the Undamped Bladed Disk

These experiments and others were conducted on a model jet engine fan to determine whether it was possible to accurately determine blade damping when only a few blades were damped. For a valid test, the measured damping of the damped blades should approach the value obtained if all the blades are damped. The measured damping of the undamped blades should approach the value obtained if none of the blades are damped. It is possible for blade-to-blade mistuning and coupling to smear the damping values. The objective was to investigate when and if it is possible to conduct a valid test using a mix of blades.

It is impractical to conduct a spin test with a mix of blades and achieve accurate results. The tests were highly optimized laboratory modal tests. Multiple excitation sources were used to resolve the closely spaced frequencies. Extreme care was taken to minimize perturbations. High fidelity response measurements were recorded. Yet some of the measured damping factors were in error. Even with the

laboratory conditions, damping smearing and localization occurred when least expected. The most promising method for testing repeated structures is gross detuning. When tip masses were added to the other blades, the damped blades were completely localized. Frequencies and damping factors were easily measured in the laboratory using a single response measurement location, a single excitation source, and simple modal estimation methods.

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6.1.3 Centrifugally Loaded Viscoelastic Material Characterization Testing

FY 96-98

CSA Engineering was tasked to characterize the behavior of viscoelastic material under centrifugal loads. While a great deal of work was done characterizing and measuring the Poisson's ratio of representative viscoelastic material in the laboratory environment, only the results of exposing viscoelastic material to centrifugal loads in a spin test are discussed here. Two types of blades were spun. The purpose of the first type of blade (shown in Fig. 33) was solely to study the effect of quasi-static centrifugal loading on viscoelastic material. The material, cast in a pocket, was subjected to up to 25,000 G's. The predicted strain over the pocket compared well with measured strain.

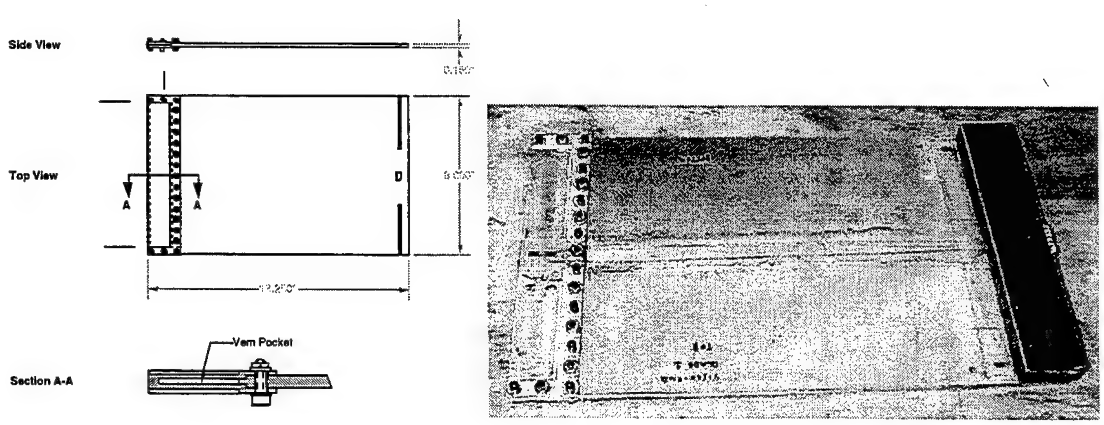


FIGURE 33. Viscoelastic Tub Blade Hardware

The second type of blade was designed to study the issues involved with damping fan blades cost effectively. The developed blade, shown in Figure 34, had a 1.5 aspect ratio. The blade consisted of two face sheets, the thicker of which had two 0.050-inch deep cavities that could be left empty or filled with viscoelastics. The sheets were held together with bolts and epoxy. The blade was instrumented with strain gages and piezoelectric patch (PZT) actuators.

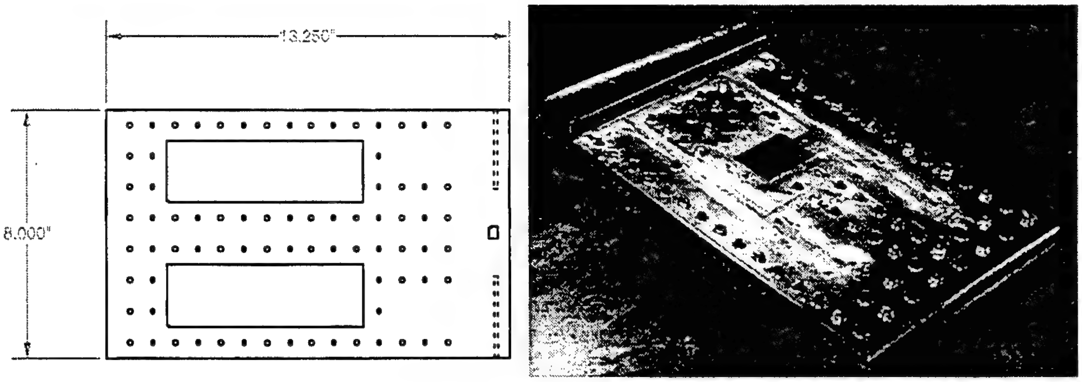


FIGURE 34. Damping Study Blade

The spun blade had one cavity filled with viscoelastic material and one empty cavity. This allowed further study of the effects of quasi-static stress on face sheets containing viscoelastics. A comparison of measured vs. predicted strain is shown in Figure 35. The measured strains for the full cavity are consistently higher than those for the empty one, as predicted. This blade was also exposed to 7,500 RPM, or the equivalent to 22,000 G's at the outmost location of the viscoelastic. The effectiveness of the damping design is seen in laboratory measurements comparing the damped blade and another completely empty but otherwise identical blade (see Fig. 36). The targeted higher order modes, such as those near 400 and 700 Hz, were well damped. Damping would have been even more significant if both pockets had been full.

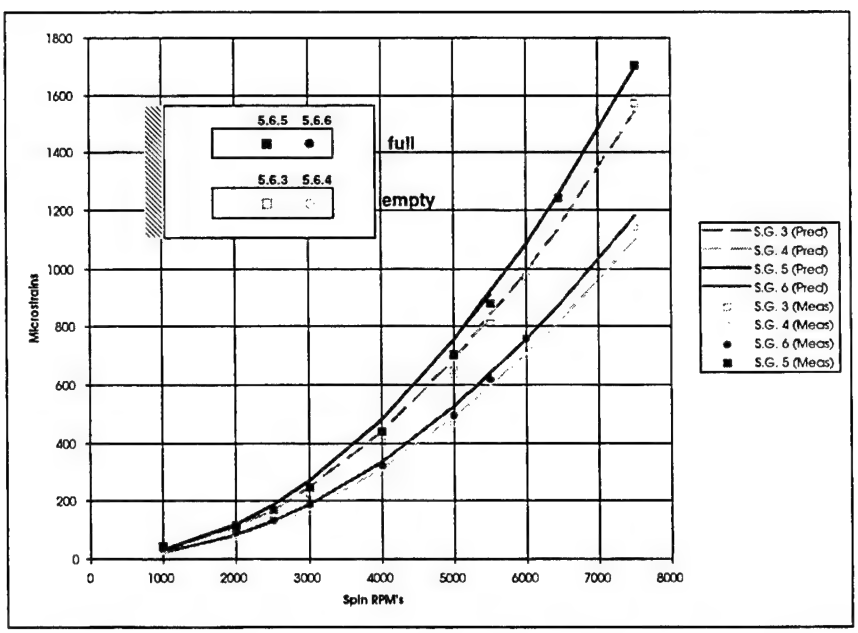
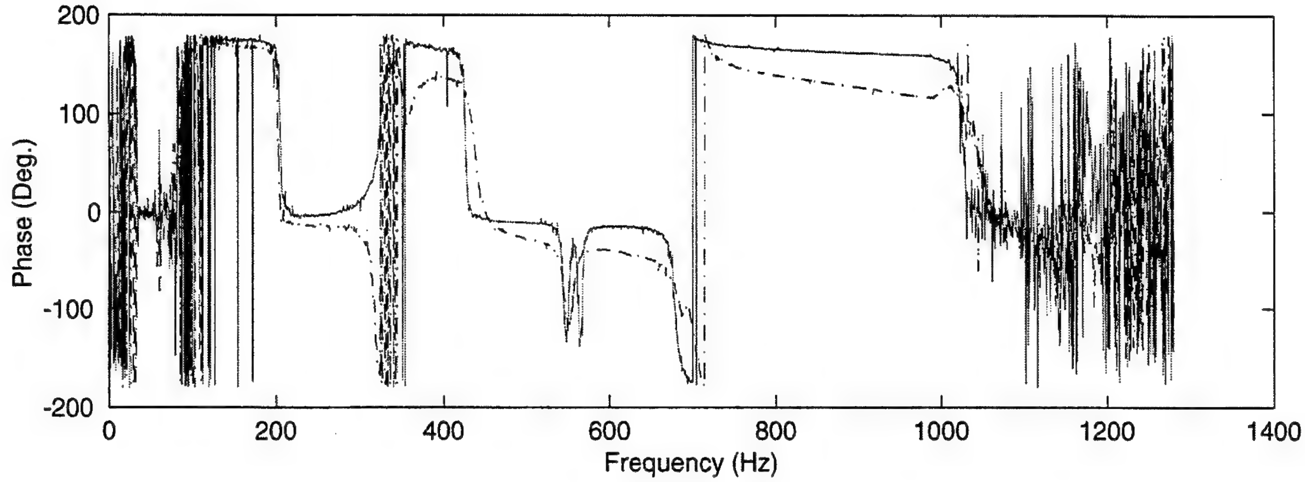


FIGURE 35. Comparison of Measured and Predicted Static Strain Over Cavity Locations for Various RPM Levels Where 7,500 RPM Corresponds to a Maximum of 22,000 G's



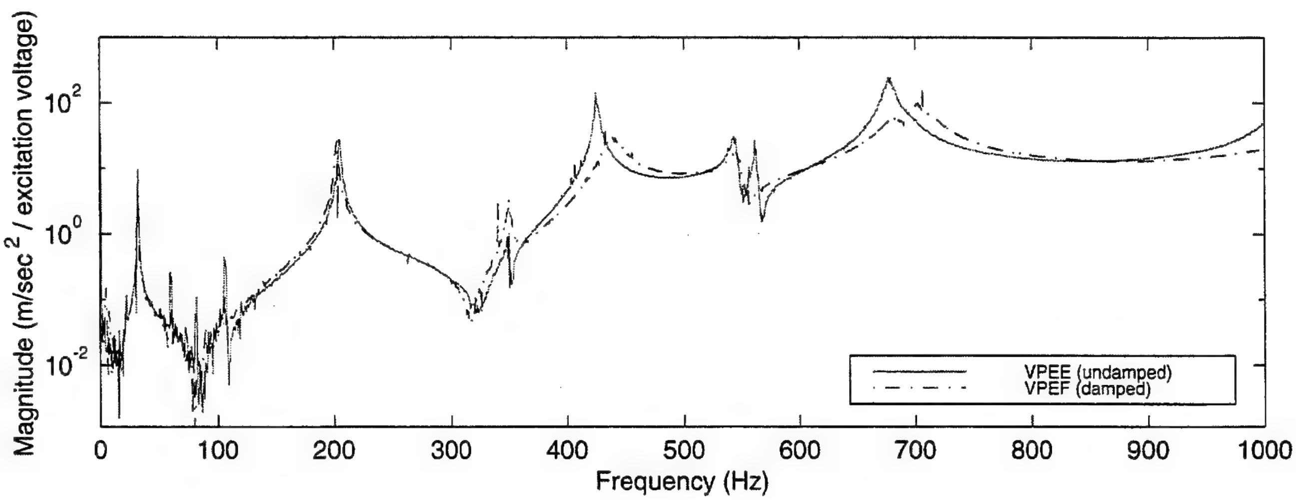


FIGURE 36. Comparison of Undamped and Damped Blade Response (One Pocket) to PZT Excitation in the Laboratory

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6.1.4 Damping for Extreme Environments

FY 97-00

DESCRIPTION / PROGRESS

The objective of this project is to develop an understanding of how to use an enamel viscoelastic material for component damping. For high temperature applications, multi-particle impact damping (MPID), unlike viscoelastic, vitreous enamel, or friction damping, offers the possibility of a solution that is rugged, reliable, and simple to implement. Numerous new ceramic materials are available for fabrication of particles. These ceramics and others offer resistance to temperature, corrosion, or thermal aging. CSA Engineering and the University of Dayton Research Institute (UDRI) have developed a first-order analytical model of a single degree-of-freedom (SDOF) system for a single particle impact damper (SPID). Indications are that an MPID system can be modeled using an equivalent SPID model.

Most previous research in the area of particle damping has borrowed its definition of damping from linear system theory. In experiments where vibration in a base structure has been dissipated through particle motion, damping has been characterized by peaks in "frequency response" or "transmissibility" functions, measured functions that assume output from a system is linearly related to the system's input. Damping is defined in two ways: (1) as a scalar value and (2) as a function of frequency. The scalar definition involves average values for system power and energy. As a function of frequency, the damping definition calls for expressions of power and energy as functions of frequency. Damping definitions that are contingent upon system power, system energy, and frequency are suitable for characterizing any system, whether linear or nonlinear.

Eight parameters of MPID systems were examined experimentally:

1. Damper Cavity Size
2. Particle Size
3. Particle Shape
4. Particle
5. Elastic Modulus of Particles
6. Mass
7. Force Level
8. Friction

CSA and UDRI performed analyses and experiments using a cantilever beam. Because the experimental results indicated significant damping for certain particle damper configurations, the second fundamental bending mode of the beam was examined analytically. Harmonic excitation at the undamped resonance was used to excite the system. Significant damping was observed at different mass ratios, with and without the effects of external friction included. Damping effectiveness increased as the mass ratio increased. Under random (white noise) excitation, the system was driven such that the primary mass RMS displacement was the same as that under harmonic excitation. The reduction in peak response under random excitation was significantly less than the reduction under harmonic excitation. This trend was expected because the energy exists at a specific frequency under harmonic excitation, while the energy is spread over a frequency range under random excitation.

Two sets of tests have been conducted at CSA, one involving motion from eight stainless steel particles in a damper cavity, and one involving a single stainless steel particle of mass equivalent to the total mass of the group of eight. In all cases, damping provided by the group of particles is significantly greater than that provided by the single particle. As cavity size decreased, system damping offered by motion of the single particle increased while that offered by motion of the group of particles decreased.

Refinements to the first-order analytic model are necessary to ensure that the significant effects of the particle dampers are captured. In the Phase II effort, particle-particle and particle-wall impacts are being modeled using the finite element code, X3D. Modifications to X3D are being made to account for rotation and momenta created due to shear forces resulting from impacts.

A resonant test beam is being used to perform damping measurements for various particles. Damping measurements have been made at severe frequencies and power levels. A high-temperature test chamber is under development for resonant beam testing. Also, a non-resonant test system is under development for measuring the damping of particles. A load cell, accelerometer, and particle cavity have been placed on the head of a shaker. This type of system is much easier to model analytically than a resonant system. The system also allows any orientation with respect to gravity to be measured. To date, load cell issues have prevented any data acquisition.

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6.1.5 Centrifugally Loaded Particle Damping

FY 96-99

DESCRIPTION / PROGRESS

Particle dampers are promising for engine turbine, compressor, and fan blade applications, as they have the capability to withstand the extremely high temperatures inherent with operational aircraft engines. There are, however, concerns that the large centrifugal loads that the particle dampers would experience in engine blades might prevent their effective operation. Thus the primary thrusts of this STTR Phase I project were to demonstrate if the behavior of particles under centrifugal loads could be predicted and to experimentally show damping under centrifugal loads. The culmination of this work was a series of spin tests performed on 9 different particle types and fill ratios at different G load levels. The best performing particle damper, based on Tungsten Carbide granules, was proof tested to more than 50,000 G's with no measurable effects on the particle composition. Detailed damping level tests were performed up to 5,000 G's in multiple RPM steps as discussed below.

Example results of the measured damping effectiveness, in terms of peak response reduction, are shown in Figure 37. These results are for the first torsional mode and were averaged from broad band tests performed at three excitation levels. One can see that as the G loading increases there is an initial decrease in damping performance (the negative value around 1,500 G's indicated there is some scatter in the damping extraction methods) followed by a gradual increase in particle damping effectiveness. The interplay of various parameters such as fill ratio, particle size, shape, and material on achieved damping levels were investigated with nine different particle damping configurations up to 1,700 G's.

To accomplish program goals, it was necessary to design and manufacture a specialized blade-like test object (Figure 38). The system was sized to withstand up to 13,000 RPM, equivalent to 70,000 G's, at the particle damping test location. Changing test configurations was simplified by the use of a removable capsule. Measurements of the inherent damping of the test object was made by performing tests on a capsule with an added fixed mass that was equivalent to the nominal particle fill mass.

To achieve controllable excitation while rotating, the blade was instrumented with piezoelectric patches. These patches also provided a high voltage response signal as compared to the millivolt traditional strain gage response. This distinction is important as it proved quite difficult to avoid cross talk between the PZT excitation drive signal and the strain gage response signals due to the need to bring the instrumentation wiring up through a narrow spindle to a slip-ring.

Based on these promising results, further investigation is warranted. It is planned to continue to develop analytical predictive capabilities, and expand the range of tested particle damping parameters to include additional particle types, sizes, finishes as well as cavity parameters. This work should be started in late FY 1998 under a Phase II STTR that is currently under negotiation.

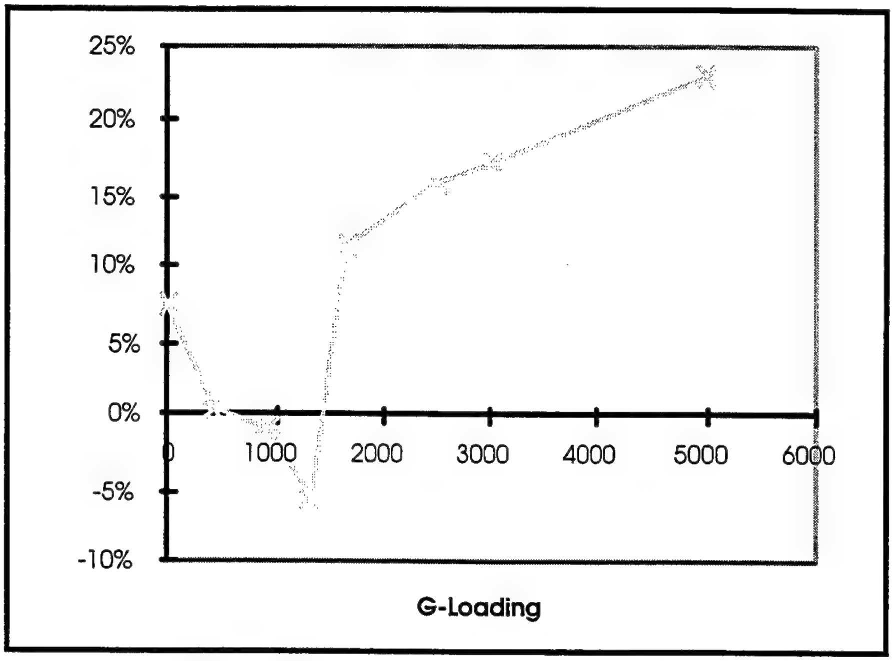

FIGURE 37. Example Measured Damping as Evidenced by Peak Response Reduction for Various G-Loading Levels

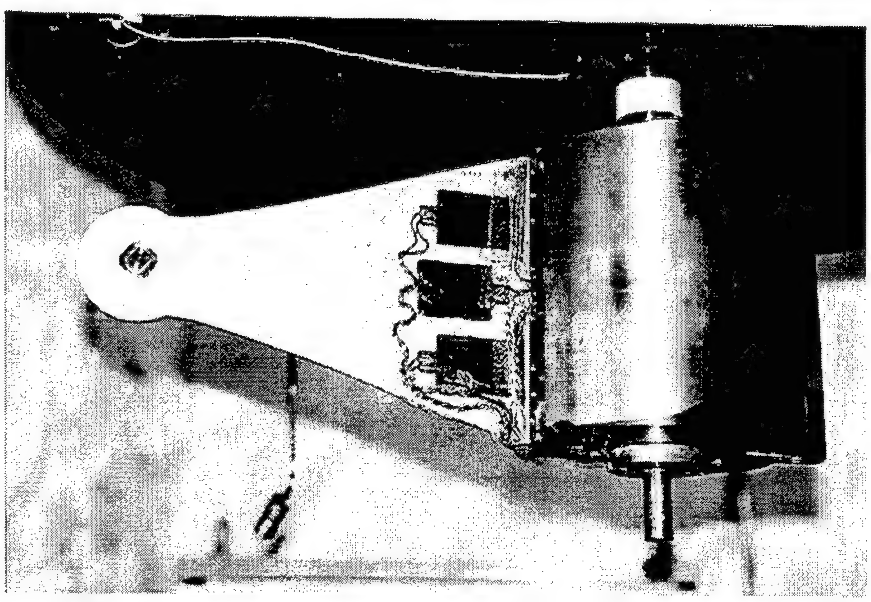

FIGURE 38. View of Test Hardware Showing Removable Capsule, PZT Excitation and Sensing Patches, Blade, and Hub

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6.2 *Modeling and Incorporation of Damping in Components*

Of the four types of damping systems (friction dampers, viscoelastic damping systems, particle dampers, and powder damping systems), two were ready for use in the design of rotating components: friction and viscoelastic damping systems. A program was initiated to use friction dampers for lower-order modes and to establish their ability to damp higher-order modes. Although there were some concerns with using viscoelastic materials, it was decided that a design program should be started while final characterization of viscoelastic materials was pursued. Component design work for particle and powder damping systems was considered premature, due to a lack of knowledge and a lack of confidence as to the likely performance of either system in a centrifugal environment. Design and testing of components with these systems will occur in the future.

6.2.1 Advanced Damping Concepts for Reduced HCF

FY 96-99

DESCRIPTION / PROGRESS

The objective of the project is to design damping into integrally bladed rotors. The new damped design will then be validated with a spin test.

Information has been gathered to define damping level requirements and the operational environment for a damping system. Team members Pratt & Whitney and AlliedSignal Engine Company. have provided environmental definition information including operating speeds, temperatures, and frequency ranges. They also have provided documentation regarding current and future blade systems and finite element models of typical blade designs.

A literature search has been performed to augment the information provided by the engine manufacturers. In addition to the archive of literature maintained at UDRI, over 50 documents directly relating to damping turbine engine structures have been obtained. The literature review has been broken into the following basic topical areas: Viscoelastic Dampers, Friction Dampers, Powder-Lubricated Dampers, Particle/Impact Dampers, Tuned Dampers/Dynamic Absorbers, General Blade Design/Analysis, and Miscellaneous Blade Damping Related. A bibliography of collected literature, along with a brief discussion of pertinent results in each of the basic topical areas, has been compiled.

A preliminary list of damping materials suitable for fan applications was established. Materials were identified based on an assumed operating temperature range of 150°F to 300°F and at frequencies of 400 Hz (corresponding to a lower order mode) and 4,000 Hz (corresponding to a higher order mode). These temperatures and frequencies were based on the operational environment information provided by team members Pratt & Whitney and AlliedSignal Engine Company. Seven promising damping materials were identified.

Numerous candidate damping designs for hollow fan blades were identified. The designs were evaluated for their potential of meeting the requirements for successful operation in a turbine engine fan system. Factors such as damping effectiveness, manufacturability, survivability, design/analysis capability, size, weight, risk, and cost were evaluated.

Four damping concepts were selected for detailed evaluation. The four concepts consist of internal cavity damping, a damping pocket with a cover plate, damping system encapsulation of the entire airfoil, and encapsulation of the leading/trailing edges.

Flat coupons with various internal damping system configurations were designed and fabricated for spin testing. These test articles will be spin tested at NASA Lewis. Specific objectives of the spin testing of the flat coupons are:

- Validation of the design methods used for evaluation of damping concepts for hollow fan blades;
- Determination of the effects of rotation and high centrifugal loading on damping in structures representative of hollow airfoils; and,
- Evaluation of the capability of specific concepts to prevent creep of viscoelastic materials under high centrifugal loading.

Laboratory tests were performed under non-rotating conditions. The results of these tests showed relatively good correlation between the laboratory frequency and loss factor data and the analytical predictions, as illustrated in Figure 39. Spin testing is anticipated to occur in December 1998.

To facilitate the test program, the actual fan blade test article will be a version of the full Pratt & Whitney blade that has been shortened at the root. Finite element (FE) models of the blade on which the final concept will be demonstrated were obtained from Pratt & Whitney along with a model of a full-length blade (i.e., one that was not shortened at the root). A natural frequency analysis was performed using the full-length blade model. Results of this analysis were used to validate the model relative to resonant frequencies measured by Pratt & Whitney. The FE models are currently being modified to include representations of the four damping concepts identified above.

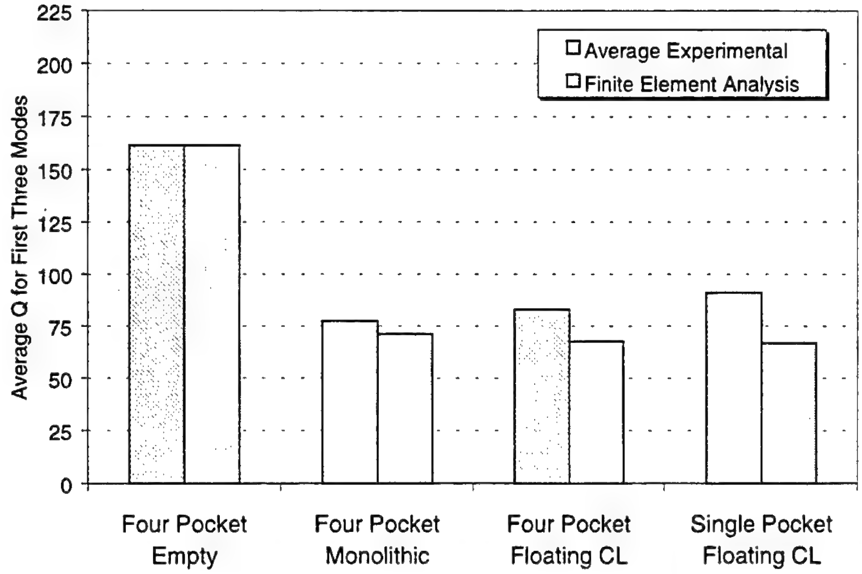

FIGURE 39. Loss Factor Correlation for Spin Test Specimens

Future emphasis in this program will be directed to the damping of solid-bladed IBRs (integrally bladed rotors).

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6.2.2 Damping System for Integrated High Performance Turbine Engine Technology (IHPTET) Program

FY 97-00

DESCRIPTION / PROGRESS

The objective of the project is to develop viscoelastic damping and particle damping for bladed rotors. Spin testing will be performed to verify the increase in damping due to the incorporation viscoelastic damping in a compressor blisk and particle damping in the blades of a fan blisk.

A program is in process to design, manufacture and spin test two passive damping systems for fan/compressor blisks. The design is complete and manufacturing has started on a constrained layer viscoelastic damping system for the Allison ACCS 1 blisk. Conceptual designs of a dry particle damping system for the General Electric XTE45 fan blisk are complete. A flat plate spin test program is currently in process, after which the detailed design of the XTE45 damping system will begin. Design analysis and limited bench test results show that a resonant amplification factor (Q) near 50 is achievable for both damping systems.

Viscoelastic Constrained Layer Damping System. Rolls Royce Allison and Roush Anatrol have completed the design of a viscoelastic constrained layer damping system (CLDS) which will be applied as an inlay to selected airfoils on an IHPTET demonstrator compressor blisk (ACCS 1, see Figure 40). ACCS 1 is a titanium 6-4 first-stage compressor blisk consisting of 16 airfoils. The tip diameter is 19.26 inches with a mid-chord airfoil span of 3.9 inches. At 75% span the chord is 6.5 inches and the maximum thickness is 0.16 inches.

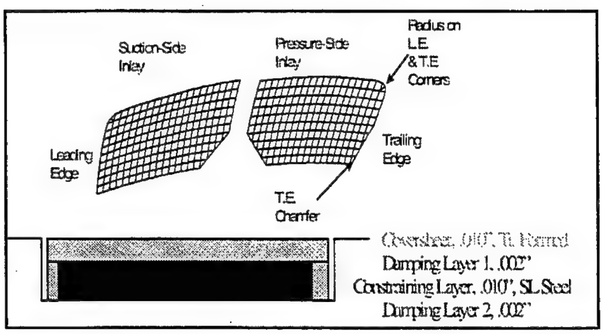

FIGURE 40. ACCS 1 Blisk

As shown in Figure 41, the specific damping treatment design for this component involves the integration of two CLDS inlays. One inlay is located on the leading edge (LE) suction side and the other on the trailing edge (TE) pressure side. Both inlays are positioned at airfoil locations in areas of maximum strain energy for the two-stripe (2S) and first torsion (1T) modes.

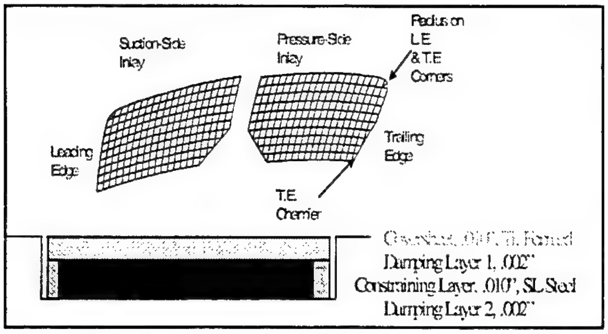

FIGURE 41. ACCS Damping Concept

The fabrication process involves machining a cavity at specific locations on the airfoil surface into which the CLDS will be inserted and bonded. A cover sheet, made of the blisk parent material, is then laser welded to the airfoil and blended to maintain the original contour. Finite element analysis predicts that the natural frequencies for the airfoils with the CLDS installed changed less than 3.5% for all modes and the mode shapes do not change significantly. The vibratory capability of the CLDS was assessed by assuming a vibratory stress level that placed the critical airfoil location (away from the damping system) at the vibratory allowable stress and then determining where the high stress areas in the damping system fell on the Goodman Diagram. This required making assumptions concerning the stress concentration and degradation in material properties in the laser weld. These assumptions will be tested by bench fatigue testing of simulated specimens. The damping materials were optimized to give maximum performance at a temperature of 200°F. The CLDS inlay design consists of a 0.010-inch titanium cover sheet, a 0.010-inch stainless steel constraining layer, a 0.002-inch inner layer of Flexcon 2078 Densil, and a 0.002-inch outer layer of Avery 1182 UHA. The predicted Q values for the first eight modes at 200°F are given in Figure 42. The effect of temperature range was estimated for the 2S and 1T modes. This system is now being fabricated into the ACCS 1 blisk and is scheduled to be spin tested in early 1999.

Mode	Damping (Q)
1	490
2 (1T)	**120**
3	91
4 (2S)	**61**
5	85
6	43
7	47
8	43

FIGURE 42. ACCS 1 Predicted Damping

Particle Damping System. General Electric Aircraft Engine Company (GEAE) and the Rocketdyne Division of Boeing have initiated the design effort for a dry particle damping system, referred to as Non-Obstructive Particle Damping (NOPD), that will be integrated into a JTDE demonstrator fan blisk (XTE45 fan, Fig. 43). The XTE45 is a titanium 6-2-4-6 first stage fan blisk consisting of 18 airfoils. The XTE45 Campbell Diagram is shown in Figure 44. The resonant crossings of interest are the 8 and 13 per rev for the 1T mode and the 13 and 16 per rev for the 2S mode.

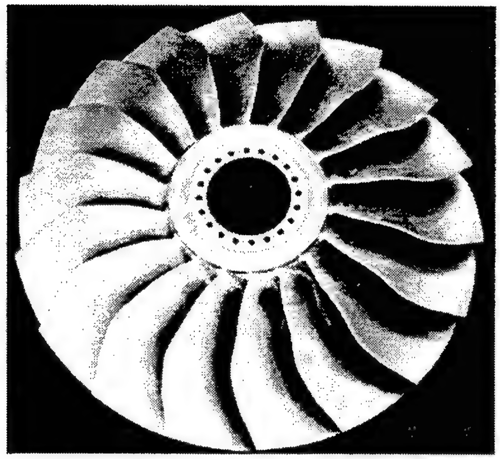

FIGURE 43. XTE45 Fan Blisk

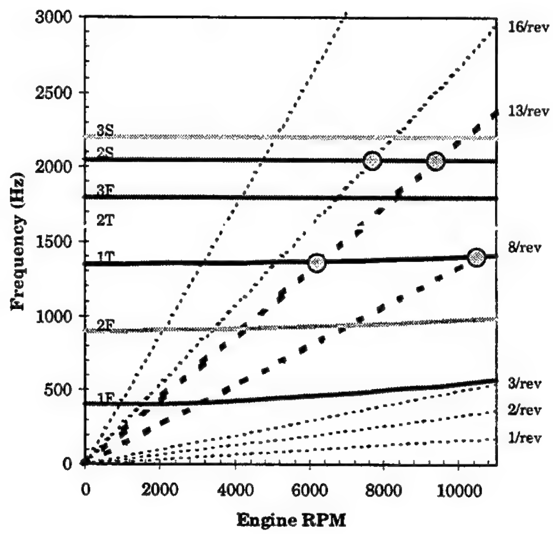

FIGURE 44. XTE45 Campbell Diagram

Conceptual studies have yielded two potential NOPD design concepts, which incorporate damping particles in the airfoil. Efforts are currently underway to conduct a spin test of the particle damping concepts at NASA Lewis Research Center. Two damping configurations, as well as baseline untreated blades, will be evaluated in flat plate test articles, which simulate the modes of interest for the XTE45 blisk airfoils. The modes of interest are 2S and 1T. Data from the spin test will be used to assess damping effectiveness and particle compaction effects. They will also serve to validate the damping system design analysis methods.

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General Electric Aircraft Engines, Rolls Royce Allison, Roush Anatrol, and Boeing/Rocketdyne

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6.2.3 Evaluation of Reinforced Swept Airfoils / Internal Dampers

FY 96-99

DESCRIPTION / PROGRESS

The objective of this project is to develop and spin test a friction damper for fans. The internal friction damper was designed and analyzed to maximize the damping characteristics of this damping system. The primary function of this design was to demonstrate its effectiveness in reducing the vibratory responses of selected high order modes.

All work on the damper has been completed except for spin testing. A finite element design utilizing the friction damper was completed. A damping prediction analysis was performed on the component. The results of this analysis are provided in Figure 45.

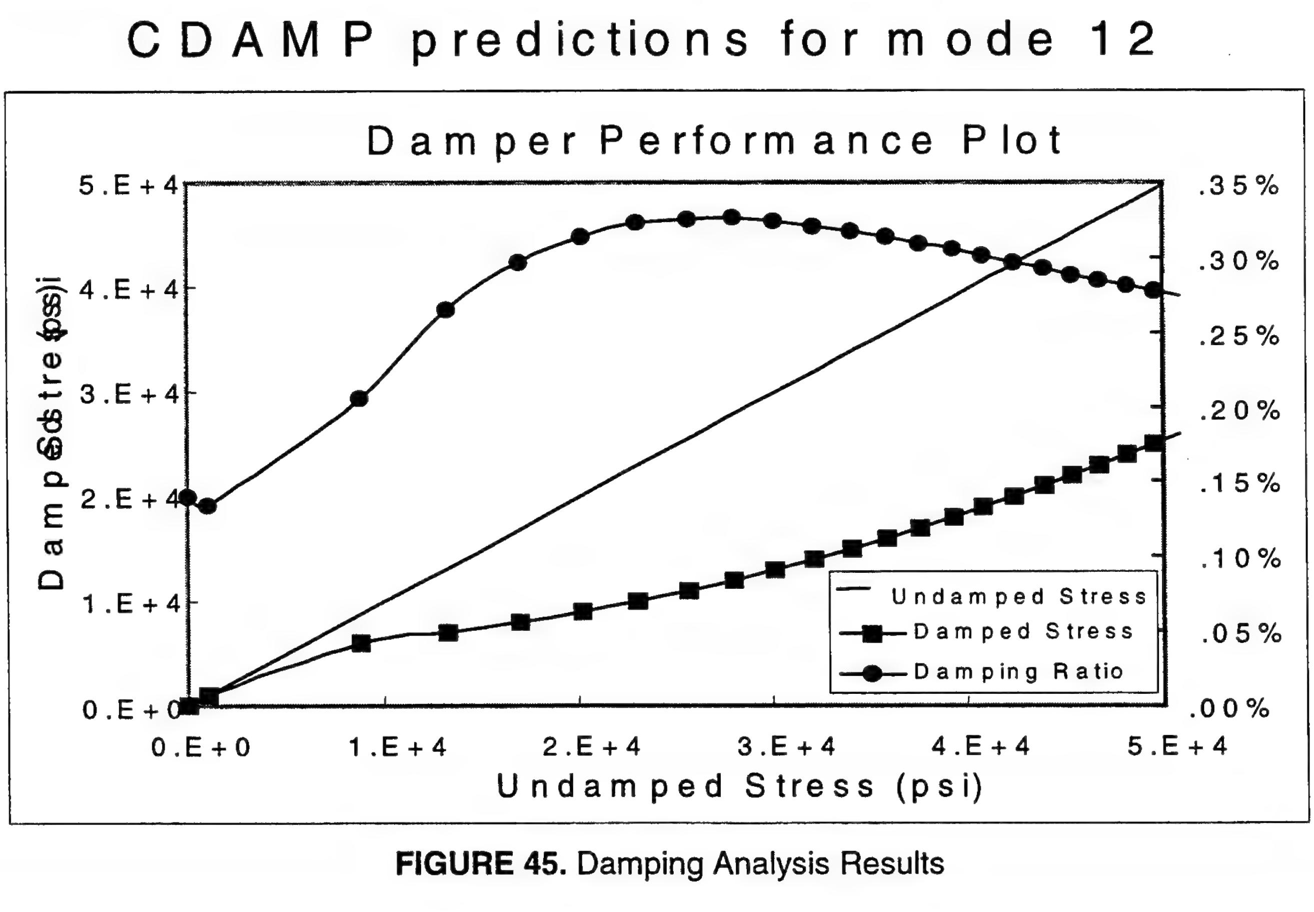

FIGURE 45. Damping Analysis Results

The analytical model was verified with static bench test data. The spin test was placed on hold until a decision can be made on the value of accomplishing this test. It was determined that the likelihood of this component ever being placed into production was very limited. It was decided to redirect the program to look at alternative internal damping configurations. Preliminary evaluations are currently being performed.

PARTICIPATING ORGANIZATIONS

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6.2.4 Damping for Turbines

FY 97-00

DESCRIPTION / PROGRESS

The objective of this project is to develop a friction damper for turbines and an alternative damping system for turbines. Both will be verified with a spin pit test.

Advanced program requirements dictate alternative solutions to damping of turbine blades. Improvements in platform damping and internal damping are being pursued to allow higher aspect ratio blading. These approaches to damping will provide increased design space, providing more- optimal blade and turbine stage designs. The design and calibration of advanced codes is key to the introduction of these advanced concepts into tomorrow's engines.

Improvements have been made in platform damping to significantly improve blade margins based on spin testing of advanced configurations. Testing is planned for 1999 to further develop these advanced concepts and to calibrate a Pratt & Whitney microslip damping code known as CDamp.

Spin testing of internal dampers for both fundamental and higher frequency modes is currently in the planning stage. The data from these configurations will be compared to advanced damping codes.

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6.2.5 High Temperature Powder Structural Damping

FY 99-01

DESCRIPTION / PROGRESS

The objective of this project is to conduct an initial investigation of the utilization of a powder damping system in a blade design. Powder damping feasibility has been demonstrated and powder material damping characteristics are being experimentally determined. Transfer of this new technology to practical applications requires evaluation in structural elements to verify the proposed design strategies. This program will develop a high temperature powder damping design methodology for both rotating and static structural elements and design and build a powder damped cantilever beam test specimen acquired under past AF sponsorship and demonstrate the effect of powder damping in controlling blade vibratory response.

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7.0 AEROMECHANICAL CHARACTERIZATION

BACKGROUND

The Aeromechanical Characterization Action Team (Aeromechanical AT) is responsible for fostering collaboration between individual HCF programs and test opportunities with the goal of providing the required design and test verification focus for the entire HCF S&T program. The Aeromechanical AT provides technical coordination and communication between active participants involved in HCF testing technologies and the Test and Evaluation Plan under development at Arnold Engineering Development Center (AEDC). Annual technical workshops have been organized, and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-chair, and selected Aeromechanical AT members meet annually to review technical activities, develop specific goals for test and evaluation programs, and review technical accomplishments. The Chair (or Co-chair) reports to the Technical Plan Team (TPT) and National Coordinating Committee (NCC) on an annual basis. The secretary of the TPT is informed of AT activities as needed. This AT includes members from government agencies, industry, and universities who are actively involved in technologies applicable to turbine engine HCF. The team is to be multidisciplinary, with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT will change as individuals assume different roles in related programs.

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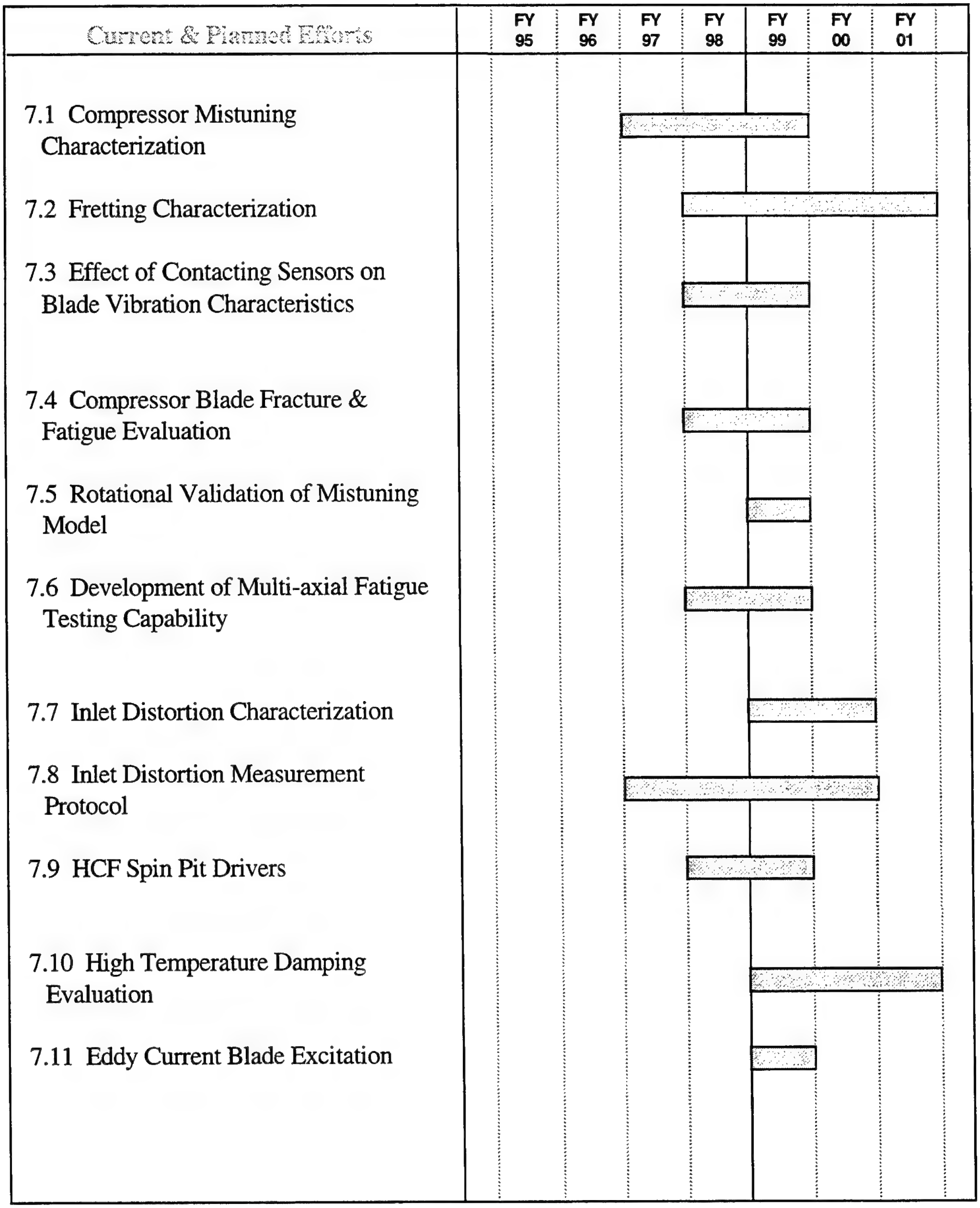
INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Aeromechanical Characterization Schedule



7.1 Compressor Mistuning Characterization

FY 97-99

DESCRIPTION / PROGRESS

The objective of this project is to characterize mistuned response at speed in an integrally bladed disk, or blisk, and compare the experimental results to a reduced-order mistuning prediction code developed under the Forced Response Action Team. Work may be extended to include traditional bladed disks using a dovetail design. The findings of this research can be used to evaluate and improve mistuning prediction codes for more accurate prediction of stresses and stress variations in fans, compressors, and turbines.

Structural variations in turbomachine blades cause variations in the natural frequencies of the blades, known as mistuning. Mistuning leads to mode localization, which makes prediction of resonant stresses difficult. Various factors, including blade structure, mechanical coupling of blades through a hub or disk, and unsteady aerodynamics, can affect the mistuned response. Measurement of the mistuned response and characterization of the factors influencing the response is necessary to develop accurate stress prediction models that account for the effects of mistuning.

The mistuned response of a high-speed compressor blisk will be characterized. Dynamic strain gages were applied to all 16 blades on the test rotor. Resonant frequencies and stresses were measured at speed for the first 3 blade modes of the rotor excited by inlet pressure distortion. Variations in frequencies and stresses were determined and compared to investigate relationships between these parameters. Mistuned response was affected by different factors for each mode. Aerodynamic damping was also measured at the first blade mode, and it was found that aerodynamic coupling dominated the mistuned response at the first blade mode. The reduced-order model aerodynamic coupling strength influence on the first blade mode is shown in Figure 46. Experimental results were be compared to predictions from a reduced-order analytical model developed under the Forced Response Action Team to gain qualitative insight into the blisk mistuned response and to determine which aspects of the modeling technique need to be improved. Predicted and measured stress variation of the first mode showed reasonable agreement, as seen in Figure 47. Comparison to the model yielded significant qualitative insight, but indicated a need for improved modeling of aerodynamic effects.

The second and third modes occurred at nearly the same frequency and were considered a coupled response. Since the third mode was more dominant, the second blade mode was difficult to characterize both experimentally and analytically. The third blade mode was strongly influenced by blade structural mistuning. Therefore, the reduced-order model developed under the Forced Response Action Team was successful in predicting the stress variations found at the third blade mode.

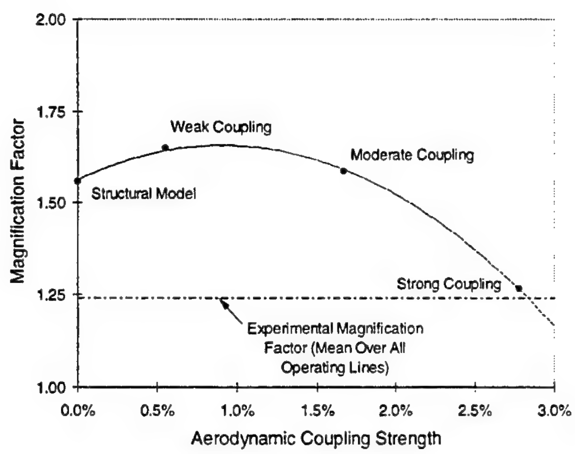


FIGURE 46. Aerodynamic Coupling Strength Influence on Response

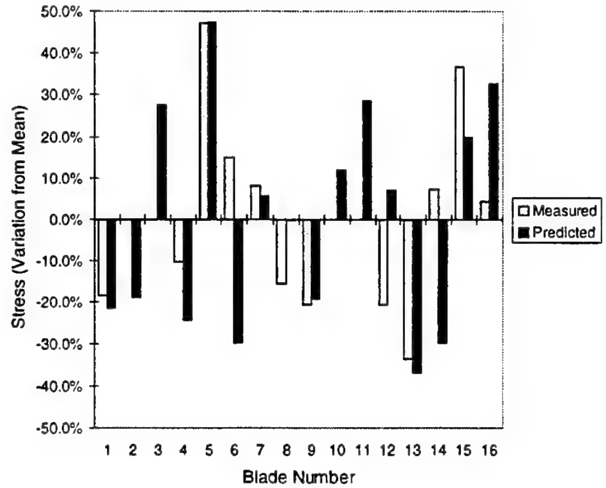


FIGURE 47. Comparison of Predicted and Measured Stress Variations for the First Blade Mode

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7.2 Fretting Characterization

FY 98-01

DESCRIPTION / PROGRESS

The objective of this project is to develop an understanding of the mechanical drivers in fretting fatigue and develop techniques to minimize their impact on material behavior. In particular the metal-to-metal dovetail attachment of blade and disk attachments will be studied. Fretting fatigue is approximately 6 percent of all HCF failures. The elimination of this problem correlates to $ 6 million per annum saved in maintenance costs.

The primary mechanical life drivers will be established through a systematic variation of various contacting bodies. The first of which will be "dog bone" specimens placed into contact by constant radius pads. Different contact loads will be applied to determine the effect of load on fretting fatigue. This will provide the basic criteria for fretting fatigue for fundamental surfaces. The second phase of the program will concentrate on real dovetailed-bladed disk geometry. Simulated contact surfaces will be loaded in a manner similar to those experienced in a turbine engine environment. The criteria developed on for fundamental surfaces will be evaluated and modified if necessary to predict fretting fatigue on the real disk geometry. Subsequent programs will then explore techniques to minimize the fretting fatigue in turbine engines.

To date, 48 "dog bone" specimens have been fabricated and tested to failure. Criteria formulation is currently under development. Fretting inserts simulating real bladed disk geometry have been machined and are ready to be tested.

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7.3 Effect of Contacting Sensors on Blade Vibration Characteristics

FY 98-99

DESCRIPTION / PROGRESS

The objective of this project is to develop a quantitative understanding of the influence of instrumentation on the vibrational response characteristics of turbine engine blades. Application of instrumentation to blades may change the structural characteristics of the host structure. A quantitative understanding of instrumentation effects on blade structures does not currently exist. Providing this understanding will lead to increased accuracy in interpretation of test data.

An initial set of six flat plate specimens has been obtained. These specimens will be structurally characterized, then instrumentation will be applied. A finite element analysis of the blade will be performed to obtain baseline vibrational and response characteristics. Each blade will be structurally characterized through dynamic ping analysis, laser holography, and SPATE. Individual blades will then be instrumented with currently available instrumentation including strain gages, high response pressure transducers, thin-film gages, and pressure/temperature sensitive paints. Once the instrumentation is applied, each blade will be structurally characterized again to determine the effect of the various instrumentation techniques on the blade response.

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7.4 Compressor Blade Fracture and Fatigue Evaluation

FY 98-99

DESCRIPTION / PROGRESS

The objective of this project is to determine the HCF enhancement of the Laser Shock Peening (LSP) process on real engine compressor blades and to quantify the enhanced Foreign Object Damage (FOD) tolerance of LSP surface treatment on real titanium compressor blades.

A series of F100-PW-229 fourth-stage compressor blades, some of which have been received instrumented, will be used to quantify the enhanced FOD tolerance of LSP. LSP-treated and untreated blades will be evaluated by being driven to failure at a resonance condition on a shaker table. FOD damage will be simulated on some of the LSP treated and untreated blades by machining a notch at the leading edge of the blade. The fatigue life of the LSP treated and untreated blades with and without the simulated FOD will be compared to determine the damage tolerance enhancement of LSP. Testing should be completed in fiscal year 1999.

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7.5 Rotational Validation of Mistuning Model

FY 99

DESCRIPTION / PROGRESS

The objective of this project is to validate the University of Michigan's reduced ordered model developed under the Forced Response Action Team. Although initial evaluation of this model was performed using engine hardware (see Section 7.1), full validation is still needed.

The reduced order modeling code has shown promise in predicting mistuning response in full engine hardware. However, full validation of the model will allow for more complete understanding of structural mistuning and for application of this code in the HCF test protocol.

Bladed disk assemblies will be intentionally mistuned based on the reduced order model predictions, and then evaluated. Validation data will be obtained from bladed disks that are rotating and non-rotating. Test data will be acquired using strain gages, holography, and SPATE in the vacuum chamber of the Turbine Engine Fatigue Facility of AFRL shown in Figure 48. Laser vibrometry will also be used on the stationary disks. The results from these mistuned disks will be compared to the reduced ordered modeling predictions.

Experimental equipment is in place at both the Air Force Research Laboratory and the University of Michigan. Design of final test articles and test plans are ongoing.

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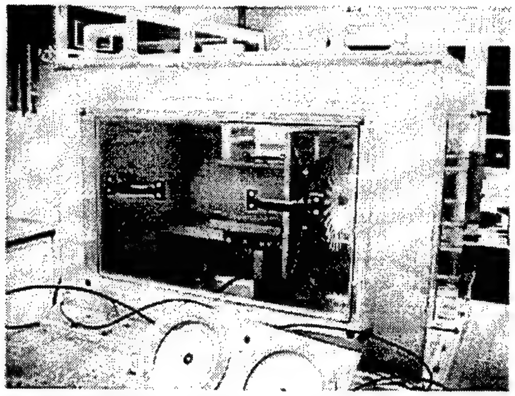

FIGURE 48. AFRL Vacuum Chamber

7.6 Development of Multi-Axial Fatigue Testing Capability

FY 98-99

DESCRIPTION / PROGRESS

The objective of this project is to develop the capability to test turbine engine components in a bench-test environment that simulates vibrational loading effects experienced during engine operation. Research goals are to develop a test system that simulates operational blade loading and to develop a data acquisition system that will accurately monitor critical test parameters. This test capability will provide a low-cost method to evaluate turbine engine blades for HCF.

A test fixture (Fig. 49) has been designed and constructed to test gas turbine blades under biaxial loading conditions. A single axis will be employed to simulate the centrifugal loading experienced by the blade. Two rams on a second axis will allow for vibrational loads in either torsion or bending. Combined, the loading allows for fatigue testing under simulated operational environments. A conceptual multi-axial fatigue model is shown in Figure 50.

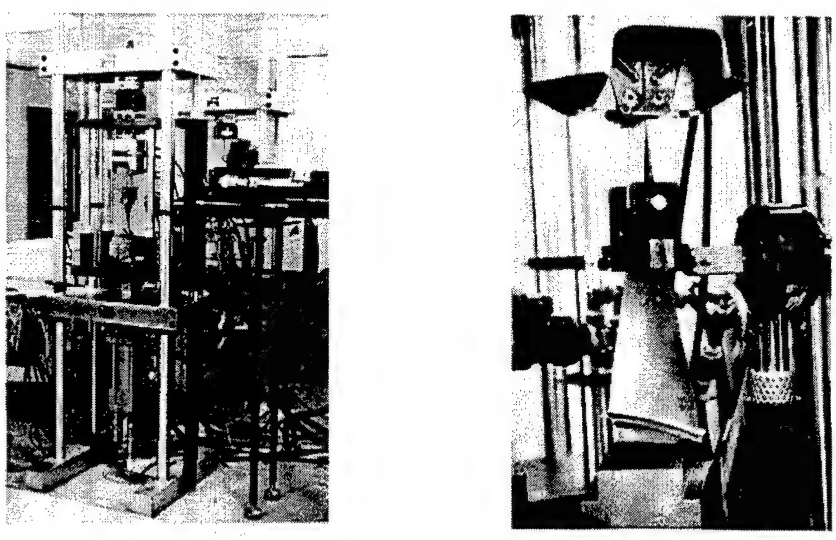

FIGURE 49. Proof of Concept Biaxial Fatigue Fixture

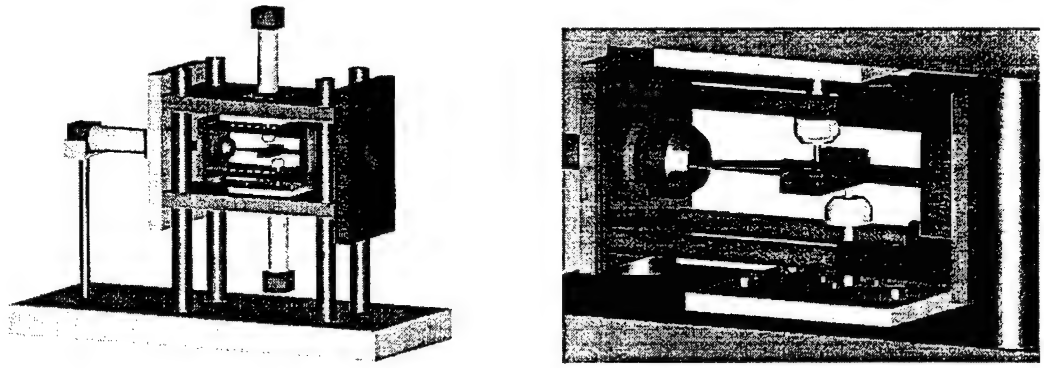

FIGURE 50. Conceptual Multi-Axial Fatigue Model

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7.7 Inlet Distortion Characterization

FY 99-00

DESCRIPTION / PROGRESS

The objective of this project is to develop a technique to produce inlet flows that simulate conditions experienced in-flight. This will improve the fan system development process for aeromechanical evaluation of blade vibrations due to inlet flow distortions.

As a result of this effort, aeromechanical risks to fan systems will be reduced by implementing a proper test and evaluation technique to simulate appropriate inlet flow field conditions, which are similar to those experienced in flight. The outcome of this program will be incorporated in the HCF test protocol.

The technical challenge is to accurately predict the inlet flow distortion and the resulting unsteady forces experienced by a fan. To develop a technique to produce inlet flows that simulate conditions experienced in-flight. An example of a three-per-rev distortion pattern using the current technology of screens is shown in Figure 51. This figure shows the intricate structure of the distortion pattern that is needed to simulate in flight conditions.

A computational and data analysis program to investigate inlet flow modeling requirements will be conducted. Analyses will be conducted of flight, ground, and model tests of the F-16/F110, and the model test data of an Advanced Compact Inlet System (ACIS) will be analyzed.

Specifically, the program will be used to develop and validate empirical and computational fluid dynamics (CFD) models using data obtained from F-16/F110 flight tests. These tools will be used to determine experimental modeling requirements for ground tests in engine and component test facilities. Predictions of the fans' vibratory stresses for this case will be compared to measurements obtained using strain gages. Also presented will be the results of a new correlation process that compares the modally-weighted integration of measured total pressures with measured vibratory stresses as applied to selected conditions from the F-16/F110 flight tests. Empirical and CFD tools for advanced systems will be evaluated and compared with model test measurements of an Advanced Compact Inlet System (ACIS).

Initial analyses of the supersonic cruise condition for the F-16/F110 flight data show good comparisons between the inlet CFD predictions and the total pressure measurements.

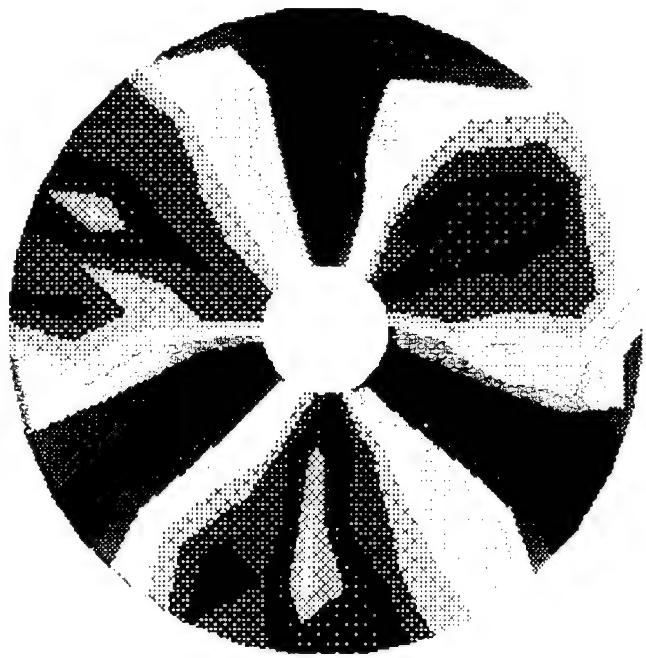

FIGURE 51. Three-Per-Rev Distortion of Total Pressure Due to Screen

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7.8 Inlet Distortion Measurement Protocol

FY 97-00

DESCRIPTION / PROGRESS

The objective of this project is to establish a new standard of inlet flow field measurement.

When turbomachinery components are evaluated for HCF resistance, the inlet flow field is frequently distorted to provide aerodynamic forcing similar to what would be present in aircraft installations. This inlet flow distortion is typically measured with 40 fixed probes that are arranged in five radial immersions at eight circumferential positions. This pattern of instrumentation has been found to adequately measure inlet flow distortion when compressors have been evaluated for stall margin sensitivity. However, for HCF evaluation, the flow field has to be more finely resolved.

In order to determine the proper technique to measure inlet flow field distortion for HCF evaluation, the inlet flow of test compressors at the Turbine Engine Research Center will be evaluated in detail. Ultimately, this new measurement concept will lead to improved HCF evaluation techniques and more reliable engines.

High-resolution measurements of inlet flow collected during two test programs have been reviewed. Several previously unknown drivers have been identified. Figure 52 is the frequency spectra of a 3/rev distortion measured with a single rake of five radial immersions that was circumferentially traversed through 360 degrees. Pressure measurements were made at 0.5-degree increments, resulting in approximately 3600 data points. Figure 53 is a pressure contour plot of the same data. The frequency spectra shows the predominate frequency is 3/rev, however, it also shows significant energy is present at 1/rev, 9/rev and 15/rev which could also excite the component being evaluated. The 9/rev frequency has been identified as the driver of a blade response that could not be explained until the 9/rev had been found. This new technique identified these additional drivers which could adversely influence the results of an HCF evaluation of the component being tested.

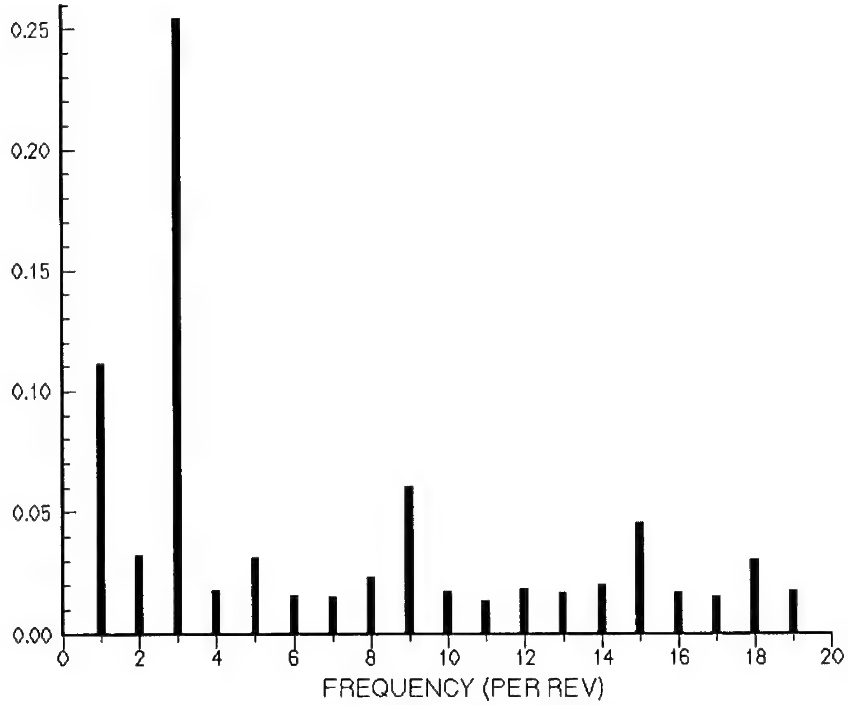

FIGURE 52. Frequency Spectra of Inlet Total Pressure

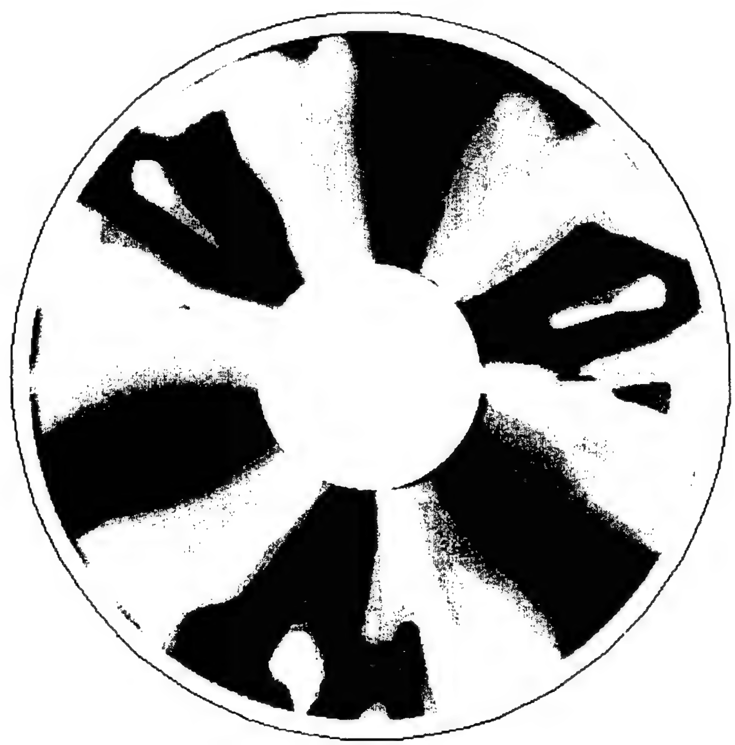

FIGURE 53. High Resolution Inlet Total Pressure Contour

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7.9 HCF Spin Pit Drivers

FY 98-99

DESCRIPTION / PROGRESS

The objective of this project is to develop techniques to enable multi-order synchronous vibration excitation of bladed rotors in conventional spin pit equipment, and to measure and record the response to such excitation so that stresses and damping factors can be determined.

The technical challenge is to achieve controlled multi-order synchronous excitation of bladed rotors in specified vibration modes at specified levels of stress in resonant conditions and at specified values of test article temperature.

The bladed portion of the rotor assembly is enclosed in a stationary shroud, in which is mounted a set of equally-spaced, radially-aligned vanes or "fences," spaced close to the leading edges of the blades. The rotor is spun at partial atmospheric pressure, typically at levels less than 1.0 psia, using nitrogen as the working fluid for safety reasons.

The complex rotating vortex flow generated in the shroud enclosure is cut, or "chopped," as it rotates past the stationary fences producing aerodynamic forces on the blades at multiples of rotation frequency, depending upon the number of fences.

The vortex flow also generates a significant temperature rise in the nitrogen, which has to be limited to prevent damage to the test parts and particularly to the rotating instrumentation. Therefore the vacuum system is run continuously to maintain the required pressure level with a significant amount of nitrogen cooling flow. The cooling flow of nitrogen gas is obtained directly from a Dewar container of LN2.

Two test programs have been carried out to date, using the first and second stage rotor blisks of the Rolls-Royce/Allison ACCS rig compressor. It has been demonstrated that the excitation system adopted will excite the blade vibration modes specified, first torsion (1T) and second chord-wise bend (2S CWB), at the specified stress levels or higher. Several harmonics of the fundamental excitation frequency could also be obtained. On ACCS Rotor 2, stress levels of 8 Ksi in resonant vibration were targeted and actual stresses of 12 Ksi were achieved. Max allowable level was 15 Ksi.

During these tests it has been confirmed that temperature control is a problem, and it has not been possible to run at constant speeds and acceptable levels of excitation for more than a few minutes. Hence, future tests will include continued development of equipment and techniques to achieve the required temperature control.

PARTICIPATING ORGANIZATIONS

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7.10 High Temperature Damping Evaluation

FY 99-01

DESCRIPTION / PROGRESS

The objective of this project is to evaluate the effectiveness and durability of various damping mechanisms at high frequency and temperature on simulated turbine blades. High temperature damping treatments that can operate and survive in a turbine blade will greatly reduce the vibratory stresses in the blade. This will reduce HCF failures and thus reduce life cycle costs of turbine engine rotating components.

Multiple damping treatments will be evaluated on flat plates in a high temperature environment while experiencing resonant vibrations. The most promising concept will then be transitioned to either a real turbine blade or a simulated blade and evaluated further in the same manner. General Electric Aircraft Engines will design and fabricate all hardware to be tested.

This effort is awaiting contract award.

PARTICIPATING ORGANIZATIONS

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7.11 Eddy Current Blade Excitation

FY 99

DESCRIPTION / PROGRESS

The objective of this project is to develop the ability to use eddy current excitation to excite rotors in a spin environment. Prediction capability and a prototype system are under development. Eddy current excitation in a spin pit will enable steady-state HCF life verification of a rotor at a fraction of the current verification cost. This capability will provide a low-cost alternative to the expensive verification tools currently in use: rig and engine testing.

A stainless steel rotor and a dimensionally similar carbon steel rotor will be spun and excited in the vacuum spin chamber. Each of the two rotors will be spun and excited with eddy current excitation in vacuum conditions. Strain measurements will be made at similar locations on each rotor in an attempt to separate magnetic force (carbon steel rotor) from the eddy current force (stainless steel rotor). This will verify the modeling approach being developed by Hood Technology Corporation.

The magnet array has been delivered to the Turbine Engine Fatigue Facility (TEFF) for implementation into the spin pit. The stainless rotor is being reworked and the derotator is being repaired.

PARTICIPATING ORGANIZATIONS

Air Force Research Laboratory (AFRL), Hood Technology Corp.

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